USING COVER CROPS TO ALLEVIATE COMPACTION IN ORGANIC GRAIN FARMS

BY

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THESIS

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ABSTRACT

Organic producers rely on mechanical operations for weed management, creating compacted areas that favor weedy species thus forming a cycle of tillage, compaction and increasing weed populations. In an effort to address the concerns of organic grain farmers from Illinois, we explored the effect of selected cover crops in compacted and non-compacted areas of their farms on weed populations, yields and soil properties in a participatory on-farm research approach. The experimental layout was a split-plot arrangement of compaction and cover crop treatments with two replications set up at four locations in Illinois. The main plot treatments were compacted (CP) versus non-compacted areas (NCP), and the sub-plot consisted of four levels of cover crops treatments: a control without a cover crop (C), forage radish (*Raphanus sativus* L.) (FR), forage radish and buckwheat (*Fagopyrum esculentum* Moench) (FRbw); and forage radish with hairy vetch (*Vicia villosa* Roth) and cereal rye (*Secale cereale* L.) (FRhvr). Farmers planted soybean (*Glycine max* (L.) Merr.) in 2012, and corn (*Zea mays* L.) in 2013 in the same plots as in 2012. Cover crop density was determined every fall prior to winterkill and spring before termination by tillage. Weed density, along with their biomass and species identification were collected prior to cash crop planting and during the growing season, while cash crop yields were determined every fall. Soil sampling was conducted each fall and spring prior to cover crop planting and termination. Penetration resistance (PR), bulk density (BD), water aggregate stability (WAS), total carbon (TC), nitrate (N-NO_3), ammonia (N-NH_4), bray phosphorus (P), and pH was determined each sampling time. Additionally, texture and Proctor determinations were conducted once at the beginning of the study. Greater PR and BD values in the CP areas verified compaction; these plots also had increased WAS, TC, P, and pH when compared to NCP areas. Cover crop treatments affected soil properties but did not alleviate compaction. Cover crops treatment additionally did not influence WAS or available nitrogen. The FR cover treatment decreased TC by 6% in the FR in comparison to the control, and the FRbw and FRhvr treatments potentially improved phosphorus cycling as decomposed FRbw increased P by 17% and still growing FRhvr decreased P by 11% in comparison to the control. Additionally, FRhvr reduced weed counts and biomass in comparison the no cover crop control, but this treatment decreased soybean yields in 2012 by 20% in the NCP. Our findings suggest the rotations with cover of forage radish/hairy vetch/rye can significantly suppress weed populations yet can potentially decrease yields, especially in dry years, and that cover crops have the potential to improve nutrient cycling, but the long term effects of the practice on compaction and carbon sequestration in Midwest organic grain systems requires further research.

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CHAPTER 1. USING COVER CROPS TO ALLEVIATE COMPACTION IN ORGANIC GRAIN FARMS: EFFECTS ON SOIL PROPERTIES

ABSTRACT

The extensive tillage necessary to manage weeds, prepare seedbeds and incorporate inputs in organic grain production requires frequent heavy machinery traffic and creates compaction that can impede productivity. To address this concern, we explored the effect of selected cover crops in compacted and non-compacted areas of organically-managed fields on soil properties in a participatory on-farm research approach. A split-plot arrangement was used with a main plot of compaction (compacted (CP) versus non-compacted (NCP) areas) and sub-plots of cover crop treatments [fallow (C), forage radish (*Raphanus sativus* L.) (FR), forage radish and buckwheat (*Fagopyrum esculentum* Moench) (FRbw), and forage radish mixed with hairy vetch (*Vicia villosa* Roth) and cereal rye (*Secale cereale* L.) (FRhvr)] with two replications at each of four Illinois locations. Soil sampling was conducted every fall and spring prior to respective cover crop planting and termination. Penetration resistance (PR), bulk density (BD), water aggregate stability (WAS), total carbon stocks (TC), available nitrogen (N-NO_3; N-NH_4) and phosphorus (P), and soil pH was determined each sampling time. Greater PR and BD values in the CP areas verified compaction; these plots also had increased WAS, TC, P, and pH when compared to NCP areas. Cover crop treatments affected soil properties but did not produce a detectable decrease in soil compaction. FR decreased TC by 6% in the FR in comparison to the control, and the FRbw and FRhvr treatments potentially improved phosphorus cycling as decomposed FRbw increased P by 17% and still growing FRhvr decreased P by 11% in comparison to the control. Available nitrogen was not significantly affected by compaction or cover crop treatments. Our findings suggest certain cover crops mixtures have the potential to

improve phosphorus cycling, but the long term effects of the practice, especially regarding total carbon, in Midwest organic grain systems requires further long-term research.

INTRODUCTION

The principles of organic agriculture center on fostering improved soil properties through biological and physical processes. Yet, organic grain production often requires extensive tillage to manage weeds, prepare seed beds and incorporate inputs. Extensive tillage on heavier soils, like Mollisols common to the Corn Belt, causes hard pans and compaction [1, 2]. Compaction, one of the most costly forms of soil degradation, affects more than 68 million ha worldwide and, in organic crop fields, can alter soil nutrient and water dynamics, reduce crop growth and yield while increasing weed problems and soil erosion [3-10].

Deep-rooted cover crops have been suggested as a way to help alleviate soil compaction. Several species of cover crops, like forage radish (*Raphanus sativus* L.) and cereal rye (*Secale cereale* L.), have elaborate root systems known to penetrate compacted soil layers, improve water and air infiltration and help subsequent crop growth in compacted areas. In a conventional corn (*Zea mays* L.) system in Maryland, Chen et al. [11] found that forage radish and rapeseed (*Brassica napus* L.) improved water and air permeability in highly compacted areas and attributed this result to the cover crop taproots ability to break up compacted soil layers. A study by Williams and Weil [12], also in Maryland, showed similar trends in a conventional no-till study where, despite drought conditions and severe compaction, soybean (*Glycine max* (L.) Merr.) yields were improved following a mix of forage radish and cereal rye. Authors suggested that the root paths created by previous cover crops and the thick mulch left by the cereal rye helped retain water and improved soybean root growth. Additionally, Villamil et al. [13] found hairy vetch (*Vicia villosa* Roth) and cereal rye to alleviate compaction by reducing bulk density and penetration resistance at the soil surface in no-till conventional corn and soybean. This result was attributed to increased root activity and soil organic matter input into the soil from the cover crops [13].

Cover crops incorporate additional soil organic matter into the soil and have been suggested as a climate mitigation tool to sequester carbon [14]. Several studies have found increased soil carbon (C) from the addition of cover crops. In a 12 year study on tillage and cover crops on erodible corn and soybean cropland in southern Illinois, Olson et al. [15] found a significant net increase in soil C at the end of the study from the addition of cover crops into rotation. Sainju et al. [16] found similar results in study observing cover crop and fertilizer treatments in tomato and eggplant production. The study found increased soil C in plots following cereal rye and a significant correlation between this soil C increase and cover crop C content, as this high biomass producing cereal rye provided large inputs of C to the soil. Additional benefits are associated with increasing soil C, such as improved soil aggregation and decreased potential for soil erosion, which is measured through water aggregate stability (WAS). Villamil et al. [13] found improved WAS with the addition of hairy vetch and rye in the no-till corn/soybean, which linked to an increased in soil C. Steele et al. [17] also found increased WAS in no-till continuous corn following cereal rye; unlike others they found no increases in total organic C but attributed the increase to interactions with fungal proteins.

Along with the potential of C sequestration and soil erosion reduction, cover crops have suggested to improve soil nutrient cycling by scavenging nutrients in the fall and making them available to cash crops in the spring [18]. In a conventional soybean study on cover crops and compaction, Acuna and Villamil [19] found reduced nitrates ($N\text{-}NO_3$) in plots with cover crops in comparison to the fallow control and attributed this reduction to the cover crops scavenging excess $N\text{-}NO_3$. Similarly, Isse et al. [20] studied cover crops, including forage radish, in sweet corn production and found cover crop plots to have reduced $N\text{-}NO_3$ in comparison to the control without over crops in fall and an increased nitrogen (N) mineralization in spring. This higher spring N did increase sweet corn yields, and they saw no effect of cover crop treatment on soil ammonium ($N\text{-}NH_4$) or phosphorus (P).

Cover crops have the potential to alleviate compaction, improve nutrient cycling and improve soil properties in cropping systems, but few studies have focused on organic grain production, especially in the poorly-drained, highly fertile Mollisols of the Midwest region. In particular for Illinois, the cold winters and the short growing season available for cover crops make this practice climate limited for the state, which may reduce the potentially benefits from the practice.

Through discussions with our project collaborators, organic grain farmers around Illinois identified soil compaction and weed suppression as major concerns. Thus a participatory on-farm research project was planned including the preferences and feedback of three experienced certified organic grain producers interested in studying the use of forage radish alone and in mixtures to alleviate soil compaction and suppress weed populations in compacted areas of their farms. Our central hypothesis was that combinations of cover crop of cereal rye and hairy vetch and buckwheat (*Fagopyrum esculentum* Moench) with forage radish would help alleviate soil compaction, improve soil nutrient cycling and better weed control. Results on the cover crop effects on weed populations and cash crop yields from this study are reported in the following chapter. The objective of our study was to evaluate the effect of forage radish alone and in mixture on soil properties in organic grain systems and deepen our knowledge on how to effectively use these multifunctional cover crops. This information is crucial for Illinois organic grain farmers, especially in the Midwest, to improve efficiency and productivity of their operations.

MATERIALS AND METHODS

Locations and Soils

Our collaborating farmers operate certified organic grain farms in three Illinois locations, where we established four experimental sites; one near Cerro Gordo (39°54’N, 88°43’W); one near Malta (41°55’N, 88°56’W); and two sites at Pana (39°27’N, 89°03’W) that were less than 2.5 km apart. The 30-year climate normal for Cerro Gordo and Pana reports from Urbana, IL, the closest weather station, is a mean annual total precipitation of 1051 mm with annual mean temperature of 10.9° C (Table 1.1). The 30-year climate normal from DeKalb, IL near Malta is a mean annual total precipitation of 939 mm with annual mean temperature at 9.1° C (Table 1.1). Farmers identified two compacted and two non-compacted areas in their fields; these were corroborated with measurements of penetration resistance and supported by a preliminary statistical analysis. Farmers agreed to plant soybean the first year (2012) and corn in 2013, keeping all treatments in the same plots the second year. In collaboration with producers, we selected the three cover crop treatments, and included a fourth control without cover crops. Additionally, farmers shared their machinery for tillage and soil preparation and were present during field selection, soil sampling and cover crop planting and suppression as well as during cash crop planting and harvesting each year.

Cerro Gordo plots were located on a farm consisting of about 650 ha farm, including about 250 ha in organic grain production. The typical grain rotation for this farm is organic corn, food grade soybeans and soft red winter wheat (*Triticum aestivum* L.). Since 1972, the farm has used a variety of cover crops, including red clover (*Trifolium pretense* L.), forage radish, cereal rye, annual rye (*Lolium multiflorum* Lam.) and oats (*Avena sativa* L.). Plots were on Flanagan silt loam (Fine, smectitic, mesic Aquic Argiudolls) on less than 2% slopes. Flanagan silt loams are dark colored, somewhat poorly drained, and form in deep loess over loamy till. Permeability is moderately low and runoff potential ranges from low to high [22]. The year prior to our study yellow organic corn was planted with 2 tons of chicken litter preceded by a mixture of cereal rye and hairy vetch as cover crops.

Malta plots were on a 770 ha farm primarily in organic grain production with 20 ha of pasture for sheep and horses and 105 ha in transition to organic production. The typical crop rotation is corn, soybean and smalls grains with several types of cover crops, including red clover, alfalfa (*Medicago sativa* L.), radishes, oats, and buckwheat. Experimental plots were on Danabrook silt loam (Fine-silty, mixed, superacitve, mesic Oxyaquic Argiudolls) with slope of about 2%. Danabrook silt loam is dark colored, moderately well-drained soil formed in deep loess over loamy till under prairie vegetation. Soils have moderate permeability and low to medium runoff potential [22]. The year prior to our study corn was planted with spring-applied manure from a local dairy.

The Pana farm is about 810 ha in total, primarily certified organic with 17 ha in transition in organic. Grain production is the main activity on the farm with some land devoted to permanent pasture for cows and pigs. The typical grain rotation is a seven year rotation of fallow, corn, oats, corn, soybean and meadow. The Pana farm uses a variety of cover crops, including white clover (*Trifolium repens* L.), alfalfa, orchard grass (*Dactylis glomerata* L.), cereal rye, hairy vetch and buckwheat. Both study sites at the Pana location were on Virden silty clay loam (Fine, smectitic, mesic Vertic Argiaquolls) with less than 2% slope. Virden is a dark-colored, poorly-drained, soil that formed in deep loess over till plains. It has moderate permeability and negligible runoff potential [22]. The year prior to our study corn was planted in both plots used in this study. For all sites, the compacted areas represented about 5% of the land and were areas with heavy machinery traffic, primarily end rows where machinery turns and that previously been stockpiled with manure in two of the studied farms.

Experimental Design

A split plot design with two replications was used at each of the four locations in two consecutive years. Main plot treatments were compaction levels (compacted, CP, and non-compacted, NCP) and subplot treatments consisted of one of four levels of cover crop treatments; a control that was left fallow (C), a cover crop of forage radish (FR), a mixture of forage radish and buckwheat (FRbw), and a mixture of forage radish, hairy vetch and cereal rye (FRhvr). Main plots measured 15 x 24 m and were approximately 15 m apart with the exception of the Cerro Gordo site which were in separate fields. The main plots were split into four 6 x 15 m subplots.

Field Methods

Cover crop planting dates, seeding rate and termination times followed the guidelines developed by the Midwest Cover Crops Council [23]. In 2011, cover crops were planted at the end of August or beginning of September, and, in 2012, the cover crops were planted in late September or early October at all sites. In 2011, cover crops at both Pana farm sites had to be replanted on October 7 due to poor stand establishment. In 2012, soybeans were planted the second or third week of May, and, in 2013, corn was planted in late May or early June at all sites. Cover crop seeding was done with hand seeders with seeding rates for forge radish (FR) of 12.3 kg/ha, forage radish with buckwheat (FRbw) was 12.3 kg/ha and 67.2 kg/ha, respectively, and the forage radish with hairy vetch and cereal rye (FRhvr) was 12.3 kg/ha, 16.8 kg/ha, and 56 kg/ha, respectively. Cover crops were terminated by spring tillage approximately two weeks prior to the cash crop planting. In 2012, the first spring tillage occurred in late March or early

April, and, in 2013, tillage was done the second or third week of May. The Cerro Gordo farmer applied 2 tons of poultry litter on May 15 in 2013 prior to corn planting. The collaborating farmer at Malta applied K_2SO_4 in fall 2011 and 1 ton of pelleted chicken manure with an analysis of 5-3-3 (N-P-K) on February 20, 2013 in advance of corn planting.

During the summer, between-row cultivation was used by all the farmers to control weeds. Following soybean planting in 2012, between-row cultivation was conducted about every month, June, July and August, until canopy closure. The farmer at Pana used 15 cm row spacing for soybean in 2012 and did not require between-row cultivation. In 2013, between-row cultivation corn started approximately a month after planting and was repeated twice about every two weeks until canopy closure at all farms.

Soil Sampling

Soil sampling was conducted four times over the course of the two-year study before and after cover crop seeding each year. In fall, sampling was conducted approximately two weeks after cover crop planting, and spring sampling was conducted approximately two weeks prior to cover crop termination by tillage in April or May at all sites. Penetration resistance (PR, kPa) was recorded with a Field Scout SC 900 Soil Compaction Meter (Spectrum Technologies, Plainfield, IL) with a cone basal area of 1.28 cm^2 and a cone angle of 30°. Five subsamples were taken per plot and were averaged to the depths of 0-5, 5-10, 10-20, 20-30, 30-40, and 40-50 cm. At the beginning of the study to characterize our experimental plots, a sample was taken with a shovel from the center of each subplot representative of the A horizon, approximately 20 cm deep, to determine the maximum bulk density (BDmax, Mg/m^3) and the particle size distribution by the hydrometer method [24, 25]. Soil texture among locations was fairly consistent; soils at all sites are classified as either silt loams or silty clay loams and were not affected by compaction treatments (Figure 1.1). The maximum bulk density is also considered an inherent soil property related to texture and carbon content [26]; values attained with the proctor test for our soils ranged from 1.38 Mg/m^3 to 1.70 Mg/m^3 and averaged 1.56 Mg/m^3. The BDmax did not differ between CP and NCP areas ($P \leq 0.2839$) or cover crop treatments ($P \leq 0.9780$). BDmax values are in agreement with the root-restricting bulk density values reported by Kaufman et al. [27] for silt loam and silty clay loam soils.

Soil samples were taken with an automated soil sampler (Amity Tech, Fargo, ND) to 50cm with three subsamples per plot. Cores were transported to the Agroecology lab at University of Illinois Urbana-Champaign and cut into depth increments of 10 cm. Soil core samples were analyzed for bulk density (BD, Mg/m^3) and water aggregate stability (WAS, %) and chemical properties of soil carbon stocks (TC, Mg/ha), N-nitrate ($N\text{-}NO_3$, mg/kg), N-ammonium ($N\text{-}NH_4$, mg/kg), available phosphorus (P, mg/kg), and soil pH. After measuring gravimetric water content at each depth, BD was determined using the core method [28] at each depht increment. Field wet soil was analyzed for $N\text{-}NO_3$ and $N\text{-}NH_4$ using KCL extraction followed by flow injection analysis with a Lachat automated analyzer (Lachat Instruments, Loveland, CO). Soils samples were then air dried and sieved by 2mm. Soil aggregates of the soil fraction between 1-2mm from the top two depths were run for WAS with an Eijkelkamp wet sieving apparatus (Eijkelkamp, Giesbeek, The Netherlands) following Kemper and Rosenau [29]. Available phosphorus was determined by Bray-1 extraction followed by flow injection analysis with Lachat automated analyzer. Soil pH (1:1 soil:water) was determined via potentiometry with a Mettler Toledo AG SevenEasy pH Meter (Schwerzenbach, Switzerland). Total carbon concentration (%) was determined by loss on ignition with a muffle furnace [30] and the results adjusted according to equations developed by Konen et al. [31] for Illinois soils.

Bulk density values were used to convert TC in % to a basis of weight per unit area, or TC stocks in Mg/ha for each 10 cm depth [32]

Statistical Analysis

Data was analyzed using the MIXED procedure of SAS software version 9.4 [33]. Compaction, cover crops and depth were considered fixed effects, while replicates (blocks within sites and sites) were considered random effects. Significance of random effects was calculated with a Wald Z test statistic using the COVTEST option in the MIXED procedure. Depth (D) was analyzed using a repeated measures technique with variance-covariance structure VC, variance components, selected on the basis of the lowest Akaike's Information Criteria [34]. Pre-planned estimates were used for mean comparison purposes setting the probability of Type I error or alpha level (α) at 0.10. The CORR procedure of SAS was used to evaluate the relationship between SOCs and WAS. Plots were created using Sigma Plot 12.5 (Systat Software, Inc., San Jose, California) and least significant difference (LSD) values at α=0.10 are included to facilitate visualization of treatment differences.

RESULTS

Fall

Fall sampling provided the baseline characterization of CP and NCP areas receiving cover crops treatments. Table 1.2 shows the exact probability values (p-values) associated with the different sources of variation in the analysis for PR, BD, WAS, TC stocks, and available N and P along with soil pH across the four sites and two years of the experiment.

Penetration resistance (PR) was significantly influenced by compaction ($P \leq 0.0021$) and depth ($P \leq 0.0001$), and, at all depths, the compacted areas (CP) had higher PR than the non-compacted areas (NCP) (Tables 1.2 and 1.3). In the CP, PR averaged 319 kPa greater than in the NCP, which was about 30% more across all depths. Additionally, PR increased with depth through the soil profile. Bulk density (BD) mirrored the PR trends. The main effects of compaction ($P \leq 0.0154$) and depth ($P \leq 0.0001$) were significant for BD. Bulk density was greater in the CP than the NCP, and BD increased through the soil profile to 20 cm and then slightly decreased as it approached 50 cm (Tables 1.2 and 1.3). These increased PR and BD values verified the compaction treatment as both properties were significantly higher in the CP than the NCP throughout the soil profile.

Similar trends were found for water aggregate stability (WAS) during the fall season. The effect of compaction was not consistent at all depths, and WAS was significantly greater in the CP areas than the NCP only at the soil surface ($P \leq 0.0076$) (Tables 1.2 and 1.3). This increased WAS in the compacted areas coincided with an increase in total carbon stocks (TC). TC was greater in CP than NCP at all depths, except at 40-50 cm, where there was no significant difference ($P \leq 0.0003$) (Tables 1.2 and 1.3). TC was about 10% greater in the CP than the NCP areas across all depths.

In regards to fall nutrient characterization, concentrations of soil nitrate ($N\text{-}NO_3$) and ammonium ($N\text{-}NH_4$) both decreased through the soil profile, reflecting nutrient stratification by depth ($P \leq 0.0001$) (Tables 1.2 and 1.3). Compaction treatments did not significantly influence available nitrogen during the fall season (Table 1.2). For available phosphorus (P), CP areas had significantly higher P than the NCP with the exception of the lower soil depths ($P \leq 0.0005$) (Tables 1.2 and 1.3). The overall effect of compaction did significantly influence soil pH ($P \leq 0.0001$) as did depth ($P \leq 0.0029$). Compacted areas had significantly greater pH than the non-compacted at all depths, and pH was about 0.41 greater in the CP than the NCP across all depths (Tables 1.2 and 1.3).

Spring

The only overwinter cover crops were the hairy vetch and rye in the FRhvr treatment, as both the FR and FRbw winterkilled prior to spring sampling. Table 1.4 shows the exact p-values associated with the different sources of variation in the analysis for PR, BD, WAS, TC stocks, and available N and P along with soil pH during the spring season across four sites after two years of initiation of experiments.

Penetration resistance (PR) in the spring season was affected by the cover crop treatments. Similar to the previous fall characterization, compacted areas has significantly greater PR than then NCP areas in all the cover crop treatments except for the FRhvr treatment, where PR did not differ by compaction ($P \leq 0.0054$) (Table 1.4; Figure 1.2A). Additionally, PR was greater than in the CP areas than the NCP areas at all depths except at the soil surface ($P \leq 0.0070$) (Tables 1.4 and 1.5;Figure 1.2B). Also, the FRbw and FRhvr cover crop treatments significantly increased PR in comparison to the control at several points within the soil profile ($P \leq 0.0810$) (Table 1.4; Figure 1.2C). Bulk density in the spring season was also influenced by the compaction and cover crop treatments. In the compacted areas, the FRhvr significantly lowered BD than FR at 0-10 cm while in the NCP FR had significantly higher BD than the control at 40-50 cm ($P \leq 0.0678$) (Table 1.4).

Following the fall trends, WAS during the spring season was significantly affected by compaction ($P \leq 0.0047$) and depth ($P \leq 0.0002$), and WAS was greater in CP than in NCP at both depths (Tables 1.4 and 1.5). Cover crops did not influence WAS ($P \leq 0.5356$). During the spring season, compaction significantly affected TC but not at all depths ($P \leq 0.0017$), and TC was greater in CP than NCP at all depths except at the lowest depth. Additionally, cover crop treatments affect TC was marginally significant ($P \leq 0.1005$), and TC was greatest in the control and FRbw and least in the FR treatment (Tables 1.4 and 1.5; Figure 1.3). TC was approximately 6% less in the FR than the control.

For available nitrogen and phosphorus in the spring following cover crop treatments, N-NO_3 and N-NO_3 significantly decreased with depth ($P \leq 0.0001$), indicating stratification through the soil profile (Tables 1.4 and 1.5). For available P, compaction ($P \leq 0.0645$), cover crops ($P \leq 0.0621$) and depth ($P \leq 0.0001$) was significant. Compacted areas had greater P than the non-compacted areas at all depths except at 30-40 cm. FRbw had the greatest P with 17% more than the control, and FRhvr had the least P with 11% less than the control (Tables 1.4 and 1.5; Figure 1.4). Soil pH significantly decreased through the soil profile ($P \leq 0.0001$) and was significantly affected by compaction and cover crop treatments ($P \leq 0.0934$). Soil pH differences were only found in the NCP, and the FRhvr treatment had the lowest pH and the control and FRbw had the highest (Tables 1.4 and 1.5; Figure 1.5).

DISCUSSION

The increased PR and BD in the CP areas verified the compaction treatment in fall, but the BD values under study were nowhere near the BDmax values found from the proctor test and were much less than the theoretical plant root restricting BD values [27]. All soils under study have shrink-swell potential and high organic matter levels, two characteristics of resilient soils typical of Illinois [22]. Soil resilience is the ability of a soil to return to previous state following a disturbance, whether that be tillage or compaction from heavy machinery traffic, and inherent soil characteristics like shrink-swell high activity clays and high organic matter content can make a soil more resilient to these disturbances [35, 36].While the compaction effect was present and consistent throughout our study sites, it was not severe or root limiting thus not expected to compromise crop yield.

Compacted areas under study had significantly increased WAS, TC, P, and pH than the NCP, especially closer to the surface, but no effect of compaction on available nitrogen was found. Primarily, these increases in the compacted areas were greatly attributed to the densification of the soil, which created more carbon and nutrients per unit area. A laboratory study by De Neve and Hofman [37] uncovered similar results from loamy sand soil incubated under varying bulk densities with and without residues. The study found the increased bulk densities to not influence nitrogen mineralization but did reduce carbon mineralization, which would allow for carbon accumulation over time. In combination with the densification, reduced decomposition rates could explain our study's increase in TC in the compacted areas. In addition, De Neve and Hofman [37] reported a strong correlation between soil carbon and water aggregate stability; in our study we determined a statistically significant yet modest correlation of TC and WAS in CP areas ($r=0.29$ $p<0.0001$)[38]. The correlation was less important in NCP areas (r=0.17, p<0.0001). As the total carbon increased, WAS was consequentially improved as soil carbon is essential for the formation and stabilization of soil aggregates [39].

Several factors influenced the observed increased in available P and soil pH in the compacted areas. Along with densification of the soil, several of these study sites had histories of stockpiling manure on these areas, which not only contributed to the compaction witnessed but potentially the available phosphorus increases. Manure applications are known to significantly increase soil phosphorus and can greatly explain the increases in the compacted areas [40, 41]. Along with P, manure application can influence soil pH, and this could be contributing to the increased pH. The literature on the effect of animal manure on soil pH is variable, and it appears this effect greatly depends on the manure source and soil type under question [41-43]. But, if animal has been fed a diet high in calcium carbonate, the manure applied can at as a liming agent and increase soil pH [41]. Another consideration on this trend is the location of the compacted areas. The compacted areas under study were along roadsides and turn rows where heavy machine traffic was frequent, and these areas were commonly in close proximity to limestone based gravel roads that could drift and cause the soil pH to increase. Most likely, this measured increased in pH in the compacted areas is not due to the compaction effect but outside factors involved in the formation of the compaction.

Cover crops treatments did have an influence on physical effects on the soil. The FRhvr roots increased PR in the NCP and reduced PR in the CP at the surface to a point where they were no longer significantly different (Figure 1.2A). The compaction by depth was still significant for PR but no longer at the surface, and this was also due to the cover crop roots activity. The FRbw and FRhvr significantly increased PR in comparison to the control at the lower depths, and this again was attributed to the interaction of the cover crop roots with the PR.

Bulk density was also influenced by the cover crops with our three-way interaction of compaction, cover crop and depth. No clear trend was identified, but, at the surface in the CP, the FR had greater BD than the FRhvr. This reduced BD from the FRhvr is attributed to the still active roots when soil sampling was conducted, but this reduction was not significantly lower than the control. Several other studies have observed compaction alleviation from cover crops, but these studies have frequently been in conventional and no-till systems [11-13]. Additionally, measuring the influence of large tap-rooted cover crops, like forage radish, on PR and BD can be difficult as the effect is localized to a small area. Elaborate fine root systems have a large area cover, which makes measuring their effects easy. But, with large taproot cover crops, our PR and BD measurement methods may not be detecting their influence on compaction as their impact is to a small area. A final consideration is the high shrink-swell potential of these study soils, which can reduce compaction overwinter and lessen the physical impact from these cover crops.

The lack of effect of cover crop on WAS contradicts some previous studies in no-till production [13, 17]. The heavy tillage used in these organic systems under study may have prevented improved aggregate stabilization from the cover crops. Additionally, these same no-till studies that reported improved WAS found increased soil carbon from the addition of cover crops [13, 17]. Our study did not find an increase in total carbon from the cover crop treatments but found a decrease in the FR treatment in comparison to the control. Most likely, the FR cover crop treatment is altering the microbial community in a way that is promoting the decomposition of TC. Further research must be done to better investigate and understand this phenomenon. Additionally, this was a short-term year study, and the lack of total carbon increase from cover crops could be due to inadequate time for carbon to accumulate from the practice. Olson et al. [15, 44] reported no net increase in soil carbon from cover crops after 8 years, but TC was higher with cover crops after 12 years. A significant soil carbon change requires an adequate amount of time having the practice in place, and our study may require further time to witness these changes. A final consideration is that soil sampling was conducted prior to tillage so the lack of cover crop incorporation into the soil could have prevented our study to find the changes in soil carbon.

In regards to plant available nitrogen, the cover crop by depth interaction was only marginally significant for $N\text{-}NO_3$, and $N\text{-}NO_3$ was greatest in the FRhvr at the lower depths. This was potentially due to the hairy vetch in this treatment fixing nitrogen. Additionally, the cover crop by depth interaction was marginally significant for NH_4, but no significant trends were identified for NH_4. Villamil et al. [13] and Isse et al. [20] found nitrates to be reduced in plots with hairy vetch and forage radish, respectively, which was not found in our study. But, similarly, Isse et al. [20] did not find an effect on ammonium. A frequently discussed benefit of cover crops is nitrogen scavenging, but, if this happened in our study, we were unable to detect it.

Conversely, available P was affected by cover crops. Along with the significantly increased P in the compacted areas, the FRbw cover crop treatment increased P by 17% while the FRhvr reduced P by 11% in comparison to the control. At the time of sampling, the winterkilled FRbw was providing more P to the system while the FRhvr was still actively growing, as it was prior to tillage, causing the P to still be retained within the plant. These two cover crops treatments, FRbw and FRhvr, are improving the phosphorus cycling for future cash crops as they draw phosphorus from lower soil depths, trap it within the plant and provide it at surface soil depths after termination for future cash crops to benefit. This effect could greatly benefit organic grain production systems that are especially deficient in phosphorus.

Finally, spring soil pH did have the significant interaction of compaction and cover crop. The significant differences were only witnessed in the NCP areas with the FRhvr having the lowest pH and the control and FRbw having the greatest. At the time of sampling, our FRhvr treatment was still actively growing as the hairy vetch and rye in the treatment did not winterkill. These actively growing roots release hydrogen ions to facilitate nutrient uptake, which can lower the surrounding soil pH, which is why we found a decrease in pH in the FRhvr [45]. The interaction of actively growing roots in the FRhvr treatment at the time of sampling and the soil is causing this measured decreased in pH from the increase in hydrogen ions in the rhizosphere.

CONCLUSION

While compaction in this study was not severe, plots chosen as compacted had higher PR, BD, WAS, TC, P and pH than did the non-compacted controls. Following the establishment of the cover crop treatments, the compaction trends on these soil properties were no longer as clear. The cover crops interacted with soil physical properties but did not definitively alleviate compaction. WAS and plant available nitrogen was not influenced by the cover crops in this study, but the FRbw and FRhvr cover crop treatments showed the potential for P capturing with their respective increases and decreases in comparison to the control, as the decomposed FRbw provided P and the still actively growing FRhvr retained P. Soil pH decreased with the actively growing roots in the FRhvr in the NCP, and, contrary to previous literature, TC was not increased from the cover crop treatments. In the FR treatment, TC was reduced by 6% in comparison to the control as the FR may be altering the microbial community and causing this decrease. The general lack of soil carbon increase from the cover crop treatment may be due to inadequate time for the practice to be in place, but more long term research is needed to better understand this phenomenon.

Previous literature has found benefits to the incorporation of cover crops into rotation. While our study found similar benefits with the phosphorus cycling, the lack of effect from our cover crop treatments on compaction indicators, soil carbon stocks, and available nitrogen brings to question if the full benefits of this practice can be achieved in a Midwest organic grain system. The impact of these cover crops greatly depends on the management and environment of the system in question, and the literature is greatly lacking organic grain research, especially in the Midwest.

On-farm research can provide valuable site and system specific data to producers to educate and advise on the best management practices. Our study demonstrates cover crops as a great tool for organic grain producers but also indicates the need for further long-term research to better understand the full potential of these cover crops in this Midwest organic grain system.

TABLES AND FIGURES

Table 1.1 Thirty year normal monthly and total mean air temperature (ºC), and precipitation (mm), and departure from the mean during the 2012 and 2013 growing seasons near Cerro Gordo and Pana, (Urbana station), and Malta (DeKalb station), IL. Source: Water and Atmospheric Resources Monitoring Program (WARM) [21].

Month	Cerro Gordo & Pana			Malta		
	30-yr normal†	Departure		30-yr normal†	Departure	
		2012	2013		2012	2013
Temperature (ºC)						
Jan.	-4.0	3.7	2.3	-6.5	3.2	1.9
Feb.	-1.7	3.3	0.4	-4.0	2.8	-0.9
Mar.	4.4	8.0	-3.1	2.2	8.7	-3.9
Apr.	11.1	1.4	-0.7	9.1	0.9	-1.8
May	16.9	3.6	1.1	15.2	3.2	1.4
June	22.3	0.3	-0.5	20.8	0.9	-1.0
July	23.9	3.7	-1.1	22.8	2.0	-1.5
Aug.	23.0	0.1	-0.1	21.8	-0.9	-0.6
Sept.	19.0	-1.2	1.6	17.4	-1.7	0.2
Oct.	12.2	-1.5	0.3	10.6	-1.3	-0.1
Nov.	5.2	-0.5	-1.5	3.4	-0.3	-1.9
Dec.	-1.7	4.2	-0.9	-4.2	5.0	-2.2
Year avg.	10.9	2.1	-0.2	9.1	2.8	-0.9
Precipitation (mm)						
Jan.	52	36	19	36	-10	58
Feb.	54	-18	37	39	8	24
Mar.	73	-24	-35	58	-12	-12
Apr.	93	-57	88	83	-15	125
May	124	-34	-5	116	-35	-24
June	110	-64	25	105	-86	93
July	119	-105	-31	111	-49	-68
Aug.	100	42	-88	111	-50	0
Sept.	80	63	-67	83	-44	-48
Oct.	83	55	23	73	20	9
Nov.	93	-62	-58	69	-47	-5
Dec.	69	-4	-2	55	-3	-21
Year total	1051	-172	-94	939	-323	131

Table 1.2 Probability values (p-values) associated with the different sources of variation in the analysis of soil penetration resistance (PR, kPa), bulk density (BD, Mg/m^3), water aggregate stability (WAS, %), total carbon stocks (TC, Mg/ha), nitrate ($N\text{-}NO_3$, mg/kg), ammonium ($N\text{-}NH_4$, mg/kg), available phosphorus (P, mg/kg), and soil pH across all locations over two fall seasons.

Source of Variation	df	PR	BD	WAS	TC	$N\text{-}NO_3$	$N\text{-}NH_4$	P	pH
Compaction (COMP)	1	0.0021	0.0154	0.1027	0.0190	0.7998	0.3057	0.0010	<.0001
Depth (D)	4	<.0001	<.0001	0.2182	<.0001	<.0001	<.0001	<.0001	0.0029
COMP x D	4	0.5235	0.4052	0.0076	0.0003	0.1432	0.4656	0.0005	0.2855

Table 1.3 Soil properties of penetration resistance (PR, kPa), bulk density (BD, Mg/m^3), water aggregate stability (WAS, %), total carbon stocks (TC, Mg/ha), nitrate ($N\text{-}NO_3$, mg/kg), ammonium ($N\text{-}NH_4$, mg/kg), available phosphorus (P, mg/kg), and soil pH in compacted (CP) and non-compacted (NCP) areas at successive depths across all locations over two fall seasons. Letters indicating statistically significant differences are shown only for effects found to be significant in Table 1.2. Within a column, means followed by the same uppercase letter are not significantly different (α=0.10).

Fall Soil Properties									
	Depth	**PR**	**BD**	**WAS**	**TC**	**$N\text{-}NO_3$**	**$N\text{-}NH_4$**	**P**	**pH**
Compaction	**cm**	**kPa**	**Mg/m^3**	**%**	**Mg/ha**	**mg/kg**	**mg/kg**	**mg/kg**	**-**
CP	0-10	942	1.12	90.7b	28.5b	27.1	3.2	63.6b	6.6
	10-20	1471	1.31	87.0a	28.8b	12.8	1.4	39.8b	6.7
	20-30	1779	1.31	-	27.5b	7.5	1.1	19.5b	6.7
	30-40	1803	1.27	-	24.2b	5.3	1.0	10.4a	6.7
	40-50	-	1.26	-	21.7a	5.1	1.0	8.3a	6.8
NCP	0-10	656	1.09	86.0a	25.6a	21.9	3.4	42.9a	6.2
	10-20	1144	1.28	87.4a	25.9a	12.4	1.5	26.3a	6.3
	20-30	1396	1.26	-	23.8a	7.5	1.6	11.1a	6.3
	30-40	1526	1.24	-	22.2a	7.1	1.0	8.3a	6.3
	40-50	-	1.26	-	21.4a	7.0	1.0	7.6a	6.3
CP	0-50	1499b	1.25b	88.4	26.2	11.6	1.5	28.3	6.7b
NCP	0-50	1181a	1.22a	87.2	23.8	11.2	1.7	19.2	6.3a

Table 1.4 Probability values (p-values) associated with the different sources of variation in the analysis of soil penetration resistance (PR, kPa), bulk density (BD, Mg/m^3), water aggregate stability (WAS, %), total carbon stocks (TC, Mg/ha), nitrate ($N\text{-}NO_3$, mg/kg), ammonium ($N\text{-}NH_4$, mg/kg), available phosphorus (P, mg/kg), and soil pH across all locations over two spring seasons.

Source of Variation	df	PR	BD	WAS	TC	$N\text{-}NO_3$	$N\text{-}NH_4$	P	pH
Compaction (COMP)	1	0.0038	0.0255	0.0047	0.0054	0.7867	0.5365	0.0645	<.0001
Cover Crop (CC)	3	0.0983	0.8794	0.5356	0.1005	0.5209	0.9286	0.0621	0.1102
COMP x CC	3	0.0054	0.4036	0.3935	0.8827	0.8164	0.9337	0.5534	0.0934
Depth (D)	4	<.0001	<.0001	0.0002	<.0001	<.0001	<.0001	<.0001	<.0001
COMP x D	4	0.0070	0.7008	0.2254	0.0017	0.7210	0.9724	0.4630	0.4384
CC*D	12	0.0810	0.5338	0.7460	0.8867	0.1517	0.1212	0.7095	0.2119
COMP*CC*D	12	0.5745	0.0678	0.8431	0.2133	0.8490	0.6469	0.8479	0.9773

Table 1.5 Soil properties of penetration resistance (PR, kPa), bulk density (BD, Mg/m^3), water aggregate stability (WAS, %), total carbon (TC, Mg/ha), nitrate ($N\text{-}NO_3$, mg/kg), ammonium ($N\text{-}NH_4$, mg/kg), available phosphorus (P, mg/kg), and soil pH determined under the cover crop treatments (C, fallow control; FR, forage radish; FRbw, mix of forage radish and buckwheat; FRhvr, mix of forage radish, hairy vetch, and cereal rye) within the compacted (CP) and non-compacted (NCP) areas at successive depths. Values are reported across all locations over two spring seasons. Letters indicating statistically significant differences are shown only for effects found to be significant in Table 1.4. Within a column, means followed by the same uppercase letter are not significantly different (α=0.10).

Spring Soil Properties									
	Depth	**PR**	**BD**	**WAS**	**TC**	**$N\text{-}NO_3$**	**$N\text{-}NH_4$**	**P**	**pH**
Compaction	**cm**	**kPa**	**Mg/m^3**	**%**	**Mg/ha**	**mg/kg**	**mg/kg**	**mg/kg**	**-**
CP	0-50	1891	1.32	85.5b	27.1	8.0	3.9	25.8b	6.8
NCP	0-50	1625	1.28	82.3a	24.8	9.3	4.3	20.3a	6.3
	0-10	1155a	1.19	86.7	31.0b	17.9	5.0	58.6	6.7
	10-20	1958b	1.38	84.4	29.9b	8.3	4.4	31.3	6.9
CP	20-30	2268b	1.36	-	27.7b	5.2	4.4	15.7	6.9
	30-40	2182b	1.32	-	24.5b	4.5	3.0	8.5	6.9
	40-50	-	1.32	-	22.5a	4.2	2.9	15.0	6.8
	0-10	1012a	1.15	84.6	27.4a	19.3	5.0	46.1	6.3
	10-20	1634a	1.34	80.1	27.0a	10.8	4.7	28.4	6.4
NCP	20-30	1857a	1.34	-	25.6a	6.4	5.1	12.1	6.4
	30-40	1999a	1.28	-	22.7a	5.9	3.4	9.0	6.3
	40-50	-	1.29	-	21.3a	4.0	3.2	6.2	6.3
Cover crop									
Control	0-50	1670	1.29	83.8	26.5a	9.0	3.7	22.6ab	6.6
FR	0-50	1728	1.30	83.6	25.3b	7.8	4.3	23.2ab	6.6
FRbw	0-50	1816	1.30	85.3	26.3a	8.9	4.9	26.5b	6.7
FRhvr	0-50	1818	1.30	83.0	25.8ab	9.0	3.6	20.1a	6.5

Figure 1.1 Textural triangle showing the percentages by weight of clay (< 0.002-mm), silt (0.002-0.05-mm), and sand (0.05-2-mm) separates of the studied soils in the conventional USDA soil textural classes. Averaged soil texture is plotted for each location (Cerro Gordo, CG; Malta, MA; Pana 1, P1; and Pana 2, P2) in compacted (CP) and non-compacted areas (NCP).

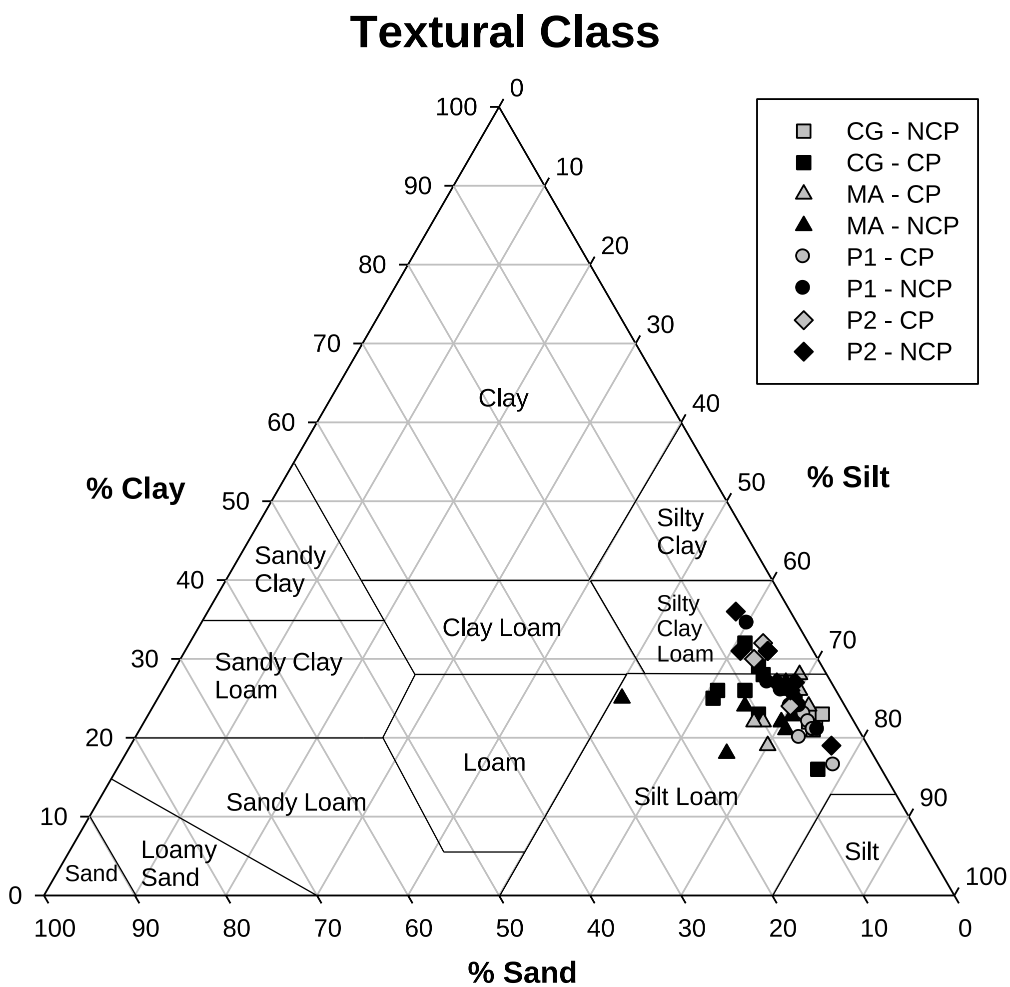


Figure 1.2 (A) Soil penetration resistance (PR) for the soils under the cover crop treatments (control, no cover crop; FR, forage radish; FRbw, mix of forage radish and buckwheat; and FRhvr, mix of forage radish, hairy vetch and cereal rye) within compacted (CP) and non-compacted (NCP) areas, across all locations over two spring seasons; and (B) Soil PR at successive depths within CP and NCP areas, across all locations over two spring seasons; and (C) Soil PR at successive depths under each cover crop treatment, across all locations over two spring seasons. (A) Letters indicate significant differences among treatment means at α=0.10. Vertical bars sharing the same letter are not significantly different as determined by pre-planned comparisons. For (B) and (C), asterisks to the side of the lines indicate statistically significant differences among treatment means at α=0.10, no asterisks indicate that at that depth, no statistically significant differences were found.

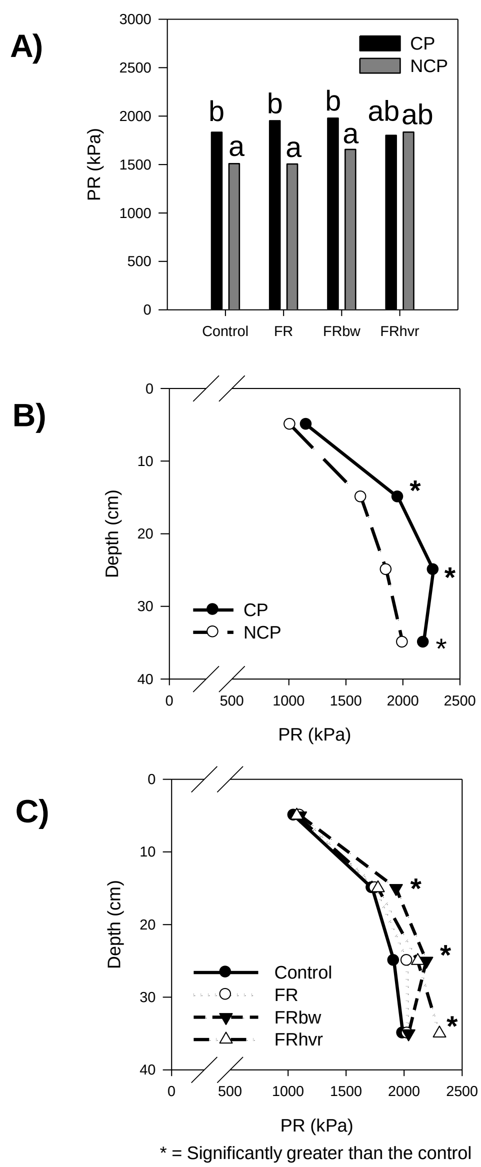


Figure 1.3 (A) Total carbon stocks (TC) at successive depths within compacted (CP) and non-compacted (NCP) areas, across all locations over two spring seasons; and (B) TC stocks under each cover crop treatment (control, no cover crop; FR, forage radish; FRbw, mix of forage radish and buckwheat; and FRhvr, mix of forage radish, hairy vetch and cereal rye), across all locations over two spring seasons. (A) Asterisks on the side of the lines indicate statistically significant differences among treatment means at α=0.10. No asterisks indicate that at that depth no statistically significant differences were found. (B) Letters indicate statistically significant differences among treatment means at α=0.10. Vertical bars sharing the same letter are not significantly different as determined by pre-planned comparisons.

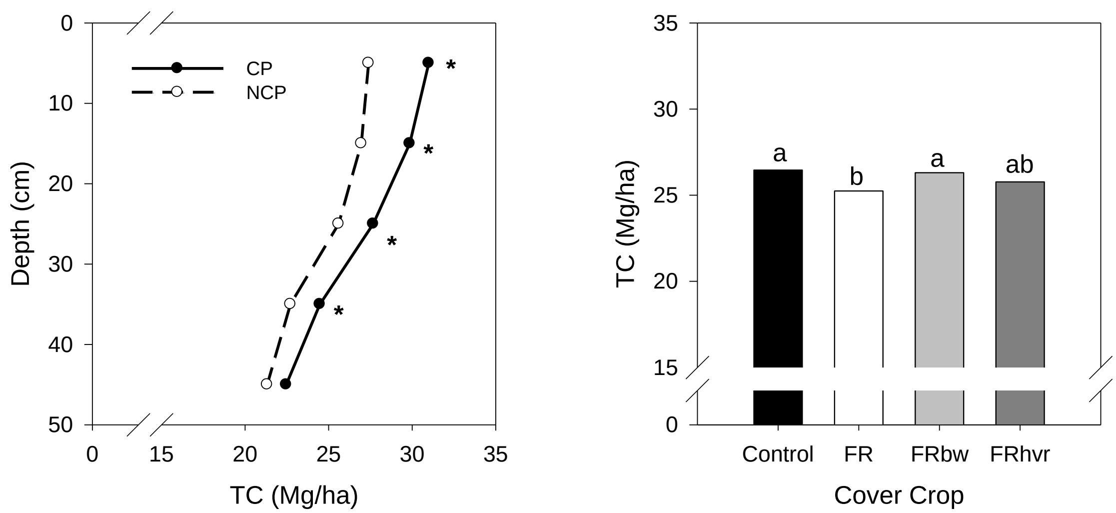


Figure 1.4 (A) Available phosphorus (P) at successive depths within compacted (CP) and non-compacted (NCP) areas, across all locations over two spring seasons; and (B) Available P under each cover crop treatment (control, no cover crop; FR, forage radish; FRbw, mix of forage radish and buckwheat; and FRhvr, mix of forage radish, hairy vetch and cereal rye), across all locations over two spring seasons. Letters indicate statistically significant differences among treatment means at α=0.10. Vertical bars sharing the same letter are not significantly different as determined by pre-planned comparisons.

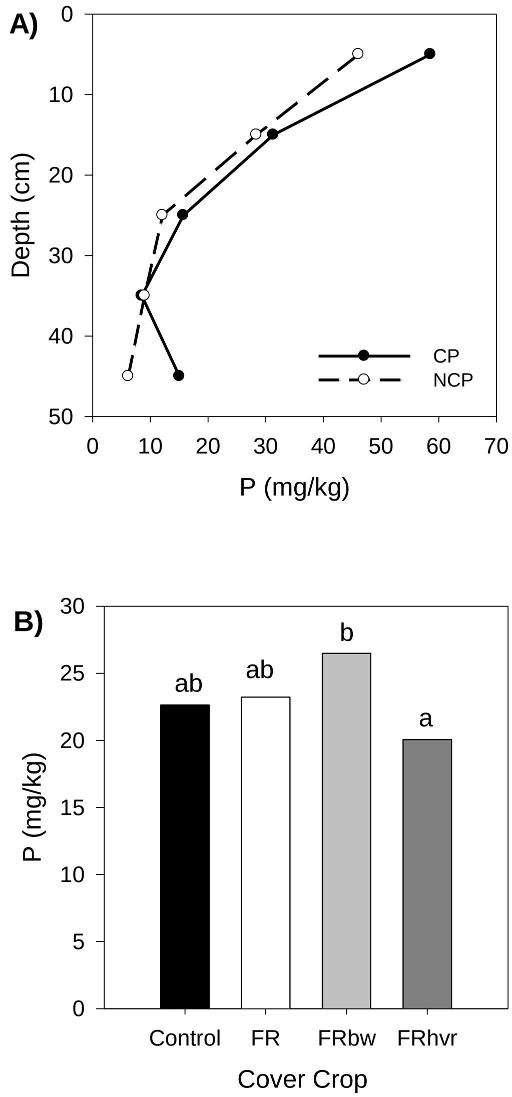
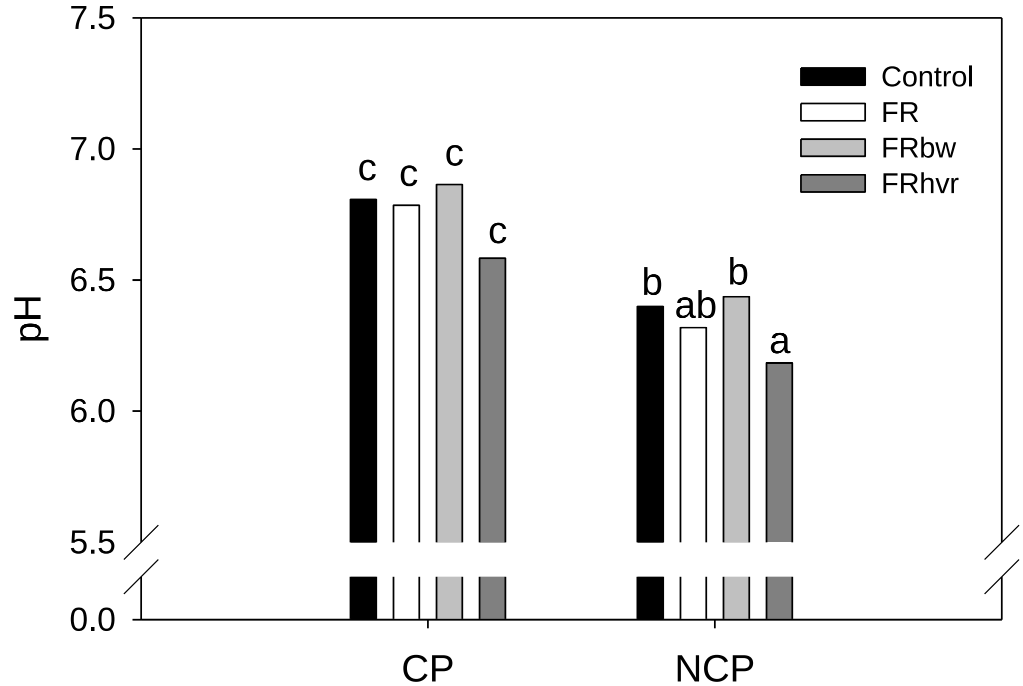


Figure 1.5 Soil pH under each cover crop treatment (control, no cover crop; FR, forage radish; FRbw, mix of forage radish and buckwheat; and FRhvr, mix of forage radish, hairy vetch and cereal rye) in the compacted (CP) and non-compacted (NCP) areas, across all locations over two spring seasons compaction. Letters indicate statistically significant differences among treatment means at α=0.10. Vertical bars sharing the same letter are not significantly different as determined by pre-planned comparisons.



REFERENCES

1. Brevik E, Fenton T, Moran L. Effect of soil compaction on organic carbon amounts and distribution, south-central Iowa. Environmental Pollution. 2002;116(1):137-41.

2. Horn R, Domzzal H, Slowinska-Jurkiewicz A, van Ouwerkerk C. Soil compaction processes and their effects on the structure of arable soils and the environment. Soil Compaction and the Environment. 1995;35(1-2):23-36.

3. Batey T. Soil compaction and soil management - a review. Soil Use and Management. 2009;25(4):335-45.

4. Hamza MA, Anderson WK. Soil compaction in cropping systems: a review of the nature, causes and possible solutions. Soil and Tillage Research. 2005;82(2):121-45.

5. van Ouwerkerk C, Soane BD. Conclusions and recommendations for further research on soil compaction in crop production. Soane BD, van Ouwerkerk C, editors. The Netherlands: Elsevier Science B. V.; 1994.

6. Jackson LE, Ramirez I, Yokota R, Fennimore SA, Koike ST, Henderson DM, Chaney WE, Calderon FJ, Klonsky K. On-farm assessment of organic matter and tillage managment on vegetable yield, soil, weeds, pests, and economics in California. Agriculture Ecosystems and Environment. 2004;103(3):443-63.

7. Ball BC, Crawford CE. Mechanical weeding effects on soil structure under field carrots (*Daucus carota L.*) and beans (*Vicia faba L.*). Soil Use and Management. 2009;25(3):303-10.

8. Ball BC, Watson CA, Baddeley JA. Soil physical fertility, soil structure and rooting conditions after ploughing organically managed grass/clover swards. Soil Use and Management. 2007;23(1):20-7.

9. Lynch D. Environmental impacts of organic agriculture: a Canadian perspective. Canadian Journal of Plant Science. 2009;89:621-8.

10. Sandhu HS, Wratten SD, Cullen R. Organic agriculture and ecosystem services. Environmental Science & Policy. 2010;13(1):1-7.

11. Chen G, Weil R, Hill R. Effects of compaction and cover crops on soil least limiting water range and air permeability. Soil & Tillage Research. 2014;(136):61-9.

12. Williams SM, Weil RR. Crop cover root channels may alleviate soil compaction effects on soybean crop. Soil Science Society of America. 2004;68(4):1403-9.

13. Villamil MB, Bollero GA, Darmody RG, Simmons SW, Bullock DG. No-till corn/soybean systems including winter cover crops: effects on soil properties. Soil Science Society of America. 2006;70:1936-44.

14. Lal R. Soil carbon sequestration impacts on global climate change and food security. Science. 2004;304:1623-6.

15. Olson K, Ebelhar SA, Lang JM. Long-term effects of cover crops on crop yields, soil organic carbon stocks and sequestration. Open Journal of Soil Science. 2014;175(2):89-98.

16. Sainju UM, Whitehead WF, Singh BP. Cover crops and nitrogen fertilization effects on soil aggregation and carbon and nitrogen pools. Canadian Journal of Soil Science. 2003;83(2):155-65.

17. Steele MK, Coale FJ, Hill RL. Winter annual cover crop impacts on no-till physical properties and organic matter. Soil Science Society of America. 2012;76(6):2164-73.

18. Dabney SM, Delgado JA, Reeves DW. Using winter cover crops to improve soil and water quality. Communications in Soil Science and Plant Analysis. 2001;32(7-8):1221-50.

19. Acuna JCM, Villamil MB. Short-term effects of cover crops and compaction on soil properties and soybean production in Illinois. Agronomy Journal. 2014;106(3):860-70.

20. Isse AA, Mackenzie AF, Stewart K, Cloutier DC, Smith DL. Cover crops and nutrient retention for subsequent sweet corn production. Agronomy Journal. 1999;91:934-9.

21. Water and Atomspheric Resources Monitoring Program [database on the Internet]. Illinois State Water Survey. 2015. Available from: http://www.sws.uiuc.edu/warm/.

22. Soil Survey Staff. Web soil survey. NRCS-USDA; 2012 [May 2014]. Available from: http://websoilsurvey.nrcs.usda.gov/.

23. Midwest Cover Crop Council. Midwest cover crops field guide [Internet]. West Lafayette, IN: Purdue Crop Diagnostic Training and Research Center; 2012 [updated 2012; cited 2015 January]. 2nd Edition. Available from: http://rusk.uwex.edu/files/2013/01/Cover-Crops-Field-Guide-2012-Inside-2.pdf.

24. American Society for Testing and Materials. Standard test methods for moisture-density relations of soils and soil-aggregated mixtures using 5.5-lb (2.49-kg) hammer and 12-in (305-mm) drop: American Society for Testing and Materials, Standards in Building Codes; 1982.

25. Gee GW, Bauder JW. Particle-size analysis. In: Klute A, editor. Methods of soil analysis, part 1: physical and mineralogical methods. Madison (WI): Soil Science Society of America; 1986.

26. Aragón A, García MG, Filgueira RR, Pachepsky YA. Maximum compactibility of Argentine soils from the Proctor test; The relationship with organic carbon and water content. Soil and Tillage Research. 2000;56(3–4):197-204.

27. Kaufmann M, Tobias S, Schulin R. Comparison of critical limits for crop plant growth based on different indicators for the state of soil compaction. Journal of Plant Nutrition and Soil Science. 2010;173(4):573-83.

28. Blake GR, Hartge KH. Bulk density. In: Klute A, editor. Methods of soil analysis, part 1. Madison (WI): Soil Science Society of America; 1986.

29. Kemper WD, Rosenau RC. Aggregated stability and size distribution. In: Klute A, editor. Methods of soil analysis, part 1: physical and mineralogical methods. Madison (WI): Soil Science Society of America; 1986.

30. Soil and Plant Analysis Council. Soil analysis: handbook of reference methods. New York (NY): CRC Press; 1992.

31. Konen ME, Jacobs PM, Burras CL, Talaga BJ, Mason JA. Equations for predicting soil organic carbon using loss-on-ignition for north central US soils. Soil Science Society of America Journal. 2002;66(6):1878-81.

32. Ellert B, Bettany J. Calculation of organic matter and nutrients stored in soils under contrasting management regimes. Canadian Journal of Soil Science. 1995;75(4):529-38.

33. SAS Institute. SAS/STAT 9.4 Production MIXED procedure for windows. Cary (NC): SAS Institute; 2013.

34. Littell RC. SAS for mixed models. 2nd ed: SAS Institute; 2006.

35. Seybold C, Herrick J, Brejda J. Soil resilience: A fundamental component of soil quality. Soil Science. 1999;164(4):224-34.

36. Blanco-Canqui H, Lal R. Soil resilience and conservation. Principles of Soil Conservation and Management: Springer; 2008. pp. 425-47.

37. De Neve S, Hofman G. Influence of soil compaction on carbon and nitrogen mineralization of soil organic matter and crop residues. Biology and Fertility of Soils. 2000;30(5-6):544-9.

38. Chaney K, Swift RS. The influnce of organic-matter on aggregate stability in some British soils. Journal of Soil Science. 1984;35(2):223-30.

39. Amézketa E. Soil aggregate stability: a review. Journal of Sustainable Agriculture. 1999;14(2/3):83-151.

40. Eghball B, Power JF. Phosphorus- and nitrogen-based manure and compost applications: corn production and soil phosphorus. Soil Science Society of America Journal. 1999;63(4):895.

41. Whalen JK, Chi C. Cattle manure amendments can increase the pH of acid soils. Soil Science Society of America Journal. 2000;64(3):962.

42. Chang C, Sommerfeldt TG, Entz T. Rates of soil chemical-changes with 11 annual applications of cattle feedlot manure. Canadian Journal of Soil Science. 1990;70(4):673-81.

43. Bickelhaupt DH. The long-term effect of a single application of horse manure on soil pH. Tree Planters' Notes. 1989;40(1):31-3.

44. Olson KR, Ebelhar SA, Lang JM. Cover crop effects on crop yields and soil organic carbon content. Soil Science. 2010;175(2):89-98.

45. Hinsinger P, Plassard C, Tang CX, Jaillard B. Origins of root-mediated pH changes in the rhizosphere and their responses to environmental constraints: a review. Plant and Soil. 2003;248(1-2):43-5

CHAPTER 2. USING COVER CROPS TO ALLEVIATE COMPACTION IN ORGANIC GRAIN FARMS: EFFECTS ON WEEDS AND YIELDS

ABSTRACT

Organic producers heavily rely on soil disturbance for weeding, creating compaction ideal for weedy species and forming a vicious cycle of tillage, compaction and increasing weed populations. To address concerns of local certified organic farmers, we explored the effect of selected cover crops in compacted and non-compacted areas of their farms on weed populations and yields in a participatory on-farm research approach. The experimental layout was a split-plot arrangement of a main plot of compaction (compacted (CP) versus non-compacted (NCP) areas) and sub-plots of cover crop treatments [fallow (C), forage radish (*Raphanus sativus* L.) (FR), forage radish and buckwheat (*Fagopyrum esculentum* Moench) (FRbw), and forage mixed with radish with hairy vetch (*Vicia villosa* Roth) and cereal rye (*Secale cereale* L.) (FRhvr)] with two replications at four locations around Illinois. Soybean (*Glycine max* (L.) Merr.) was planted in 2012 with corn (*Zea mays* L.) in 2013. Cover crop plant density was determined in the fall prior to winterkill and in the spring before termination by tillage. Weed density, biomass, and species identification were collected prior to cash crop planting and during the growing season, while cash crop yields were determined every fall. The FRhvr reduced weed counts by 37% and weed biomass by 48% in the CP and 75% in the NCP, respective to their fallow controls. While weed suppression was effective with the overwintering FRhvr, in 2012, this cover crop treatment decreased soybean yields by about 20% in NCP but had no effect on corn yield in 2013. Drought conditions during 2012 increased water stress and preceding cover crops hindered cash crops by depleting available water in the NCP areas. The CP areas reduced this effect by retaining water within their soil profiles. While we show that using a mixture of forage radish, hairy vetch, and

rye cover crops can significantly suppress weed populations, their effect on cash crop yields may not always be positive, especially yields in dry years.

INTRODUCTION

Despite consumer demand and premium prices, adoption of organic practices for grain production has been slow and consequentially limited the expansion of organic livestock in the U.S [1]. One of the main barriers to the expansion of organic management in grain crops is weed control [2, 3]. Weed populations compete with cash crops, decreasing yields, lowering crop quality and increasing production inputs [4]. When transitioning to organic, weed community dynamics rapidly change. Albrecht [5] and Rydberg et al. [6] both reported rapid increases in weed populations during the transition period as well as an increase in species diversity. Organic farming uses a wide range of methods to manage these changing weed populations, including diversified crop rotations, primary tillage for seedbed preparation, use of competitive crop cultivars, and intensive inter-row cultivation during the growing season [7]. Most of these methods require extensive time maneuvering in the field, heavy machine traffic, and intensive tillage of the soil, all of which can cause soil compaction, restricting root growth and reducing crop production [8]. Soil compaction negatively affects soil quality and productivity by interfering with water infiltration, nutrient cycling, root development, and aeration [9]. Overall, compaction can greatly decrease the yield potential of cash crops. Botta et al. [10] in a study on conventional soybeans (*Glycine max* (L.) Merr.) in Argentina found compaction treatments caused by heavy machinery traffic reduced soybean yields about 15% over the course of three years. In a Pennsylvania study in conventional corn (*Zea mays* L.), Sidhu and Duiker [11] reported similar results indicating compaction from heavy machinery traffic greatly reduced yields, especially under stressful growing conditions. Reintam et al. [12] and Place et al. [13] found soil compaction limits a cash crops ability to compete with weedy species as they more effectively scavenge valuable nutrients and are more tolerant to poor environmental conditions. With more weeds emerging, more cultivation and management is required, creating a negative cycle of tillage, compaction and increased weed emergence. Breaking this cycle is essential to improving organic grain production, and cover crops have been suggested as a critical tool to address both issues of soil compaction and weed suppression in the field.

The alleviation of soil compaction by cover crops has been observed in several studies. In a conventional corn system in Maryland, Chen et al. [14] found forage radish (*Raphanus sativus* L.) and rapeseed (*Brassica napus*) improved water and air permeability in highly compacted areas and attributed this result to the cover crop taproots ability to break up compacted soil. A study by Williams and Weil [15], also in Maryland, discovered similar trends in a conventional no-till soybean study where drought soybean yields were improved following a mix of forage radish and cereal rye (*Secale cereale* L.) in areas where drought conditions and compaction were severe. Authors suggested that the previous cover crops created root paths that improved soybean root growth and the thick mulch left by the cereal rye help retain valuable water. While studies have found cover crops to alleviate compaction, the impact of this agronomic practice is greatly context-dependent, and few studies have focused on this effect in highly fertile soils, like Mollisols commonly found in the Corn Belt [16].

In addition to potential compaction relief, cover crops outcompete weeds for valuable water and nutrients in the soil, creating a dense canopy that block light to these weeds, and, in many cases, releasing allelopathic chemicals that suppress weed communities [17]. This weed suppression by cover crops has been corroborated in the literature. In a greenhouse study by White et al. [18], the allelopathic effect of legume cover crops, hairy vetch and crimson clover (*Trifolium incarnatum* L.), were verified as their residues were found to significantly reduce the emergence and growth of pitted morning glory (*Ipomoea lacunosa* L.). Conversely, this study found that when these residues were incorporated cotton emergence and dry weight was negatively affected, which brings concern to cover crop's benefit in production. Similarly, Dhima et al. [19] found the addition of winter cover crops, cereal rye, triticale (× *Triticosecale*), and barley (*Hordeum vulgare* L.), into a conventional corn system significantly reduced barnyardgrass (*Echinochloa crus-galli* (L.) P. Beauv.) and bristly foxtail (*Setaria verticillata* (L.) Beauv.) stem number and fresh weight. In an organic system, Uchino et al. [20] studied interseeding cereal rye and hairy vetch (*Vicia villosa* Roth) into potato, corn, and soybean production in Japan and observed these cover crops to significantly reduce weed growth in the corn and soybean systems. Past research on the suppressive effect of cover crops has primarily been in conventional or greenhouse studies. There is a need for more research on this suppressive effect in organic grain production as this research may not be applicable to an organic system.

Cover crops effect on cash crop yields is a major concern, and research has found variable results on their influence. As previously mentioned, Williams and Weil [15] found a mixture of forage radish and cereal rye benefitted conventional no-till soybean yields, despite compaction and drought conditions. Likewise, Koger and Reddy [21] researched the addition of hairy vetch into conventional corn in Mississippi and discovered that fully desiccated hairy vetch increased corn yields in comparison to plots without hairy vetch. But when hairy vetch was only partially terminated, corn yields were decreased, and this was attributed to the competitive effect of the cover crops with the corn for water. In Illinois, Miguez and Bollero [22] studied cover crops, hairy vetch and cereal rye, along with varying rates of N fertilizer in conventional no-till corn and found hairy vetch to increase corn yields in comparison to no cover crop but only witnessed when no fertilizer was used. Miguez and Bollero [23] also conducted a meta-analysis and discovered legumes and mixtures of grass and legume cover crops significantly increased corn yields across the U.S. and Canada but not in all regions. This result strongly indicates the influence of environment on the benefits from the addition of these winter cover crops in production.

Cover crops have shown benefits to weed suppression and cash crop yields, but environmental conditions and length of growing season along with management practices play a strong role in the success of these cover crops. The short growing season available for cover crops translates into inconsistent growth of cover crops in U.S. Midwest. In turn, this means inconsistent realization of the potential benefits from cover cropping.

Through discussions with our project collaborators, organic grain farmers around Illinois have identified weed management and soil compaction as two of their greatest challenges. Thus a participatory on-farm research was planned including the preferences and feedback of three experienced certified organic grain producers interested in studying the use of forage radish (*Raphanus sativus* L.) alone and in mixtures to alleviate soil compaction and suppress weed communities in compacted areas of their farms. Our central hypothesis was that combinations of cover crop of cereal rye (*Secale cereale* L.) and hairy vetch (*Vicia villosa* Roth) and buckwheat (*Fagopyrum esculentum* Moench) with forage radish would help reduce weed pressure in compacted areas without negatively impacting cash crop yields. The objective of our study was to evaluate the ability of forage radish alone and in mixture to suppress weed in organic grain systems and deepen the farmer’s knowledge and skillset to effectively utilize these multifunctional cover crops. This information is crucial for organic grain farmers, especially in the Midwest, to improve efficiency and productivity of their operations.

MATERIALS AND METHODS

Locations and Soils

Our collaborating farmers own certified organic grain farms in three different locations in Illinois where we set up four experimental sites: one in Cerro Gordo (39°54'N, 88°43'W), one in Malta (41°55'N, 88°56'W) and two sites in Pana (39°27'N, 89°03'W) that were less than 2.5 km apart. The 30-year climate normal reported from the closest weather station for Cerro Gordo and Pana is a mean annual total precipitation of 1051 mm with annual mean temperature of 10.9° C (Table 2.1). The 30-year climate normal for Malta, also from the closest weather station, is a mean annual total precipitation of 939 mm with annual mean temperature at 9.1° C (Table 2.1). All farms had a history of using cover crops in their grain rotation, and all soils under study were Mollisols formed in deep loess over till under prairie vegetation [24]. Farmers identified two compacted and two non-compacted areas in their fields that were corroborated with measurements of penetration resistance and supported by a preliminary statistical analysis (*shown in the previous chapter*). During our planning sessions, our farmers agreed on planting soybean the first year and corn the next and selected the three cover crop treatments under study, including a control without cover crops to satisfy research requirements. Additionally, farmers shared their machinery for tillage and soil preparation and were present during field selection, soil sampling and cover crop planting and suppression as well as during cash crop planting and harvesting each year.

Experimental Design

A split plot design with two replications was used at each of the four locations every year. Main plot treatments were compaction levels (compacted, CP, and non-compacted, NCP) and subplot treatments consisted of one of four levels of cover crop treatments; a control that was left fallow (C), a cover crop of forage radish (FR), a mixture of forage radish and buckwheat

(FRbw), and a mixture of forage radish, hairy vetch and cereal rye (FRhvr). Main plots measured 15 x 24 m and were split into four 6 x 15 m subplots. Soybean was planted in 2012, and corn was planted in 2013.

Field Methods

Cover crop planting dates, seeding rate and termination times followed the guidelines developed by the Midwest Cover Crops Council [26]. In 2011, cover crops were planted between the end of August and beginning of September, and, in 2012, the cover crops were planted between the end of September and beginning of October for all farms. In 2011, both Pana farm sites had to be replanted on October 7 due to poor stand establishment. In 2012, soybeans were planted between the second and third week of May, and, in 2013, corn was planted around late May and early June at all sites. Cover crop seeding was done with hand seeders with seeding rates for FR of 12.3 kg/ha, FRbw was 12.3 kg/ha and 67.2 kg/ha, respectively, and the FRhvr was 12.3 kg/ha, 16.8 kg/ha, and 56 kg/ha, respectively. Cover crops were terminated by spring tillage approximately two weeks prior to the cash crop planting. In 2012, the first spring tillage occurred between late March and early April, and, in 2013, tillage was done between the second and third week of May. The Cerro Gordo farmer applied 2 tons of poultry litter prior to corn on May 15 in 2013 with a Case IH 330 True Tandem. The collaborating farmer at Malta applied potassium sulfate in fall 2011 and 1 ton of pelleted chicken manure with an analysis of 5-3-3 (N-P-K) prior to corn on February 20, 2013.

During the summer, between-row cultivation was used by all the farmers to control weeds. Following soybean planting in 2012, between-row cultivation was conducted each month until canopy closure. The farmer at Pana used 15 cm row spacing for soybean in 2012, preventing between-row cultivation. In 2013, between-row cultivation corn started approximately a month after planting and was repeated about every two weeks until canopy closure.

Vegetation Sampling

Cover crop density was determined every fall before winterkill and every spring before termination. Cover crop biomass was collected in the spring on the only overwintering treatment, FRhvr. Cover crop density and biomass was determined by randomly placing a 30 cm by 30 cm quadrat in each subplot three times and counting the plants within the quadrat. Above ground biomass was removed, oven dried at 45˚ C for two days, and weighed. In both years, fall cover crop counts occurred in the first week of November. Spring biomass sampling was done for all farms during the first week of April in 2012 and in the last week of May in 2013. Cover crop and weed data was not taken in spring 2012 at Malta due to early tillage.

Weed counts and biomass used the same quadrat sampling method aforementioned. Within a quadrat, all weeds were counted, identified to species and above ground biomass was cut at ground level, bagged and dried to constant weight. First sampling was conducted before the cash crop planting, and then two more samplings were coordinated with farmers to occur before each between-row field cultivation during the summer. In 2012, sampling was done in April, June and August, and, in 2013, sampling was done in May, June, and July.

The dominant broadleaf weed species were henbit deadnettle (*Lamium aplexicaule*), field penny-cress (*Thlaspi arvense*), chickweed (*Stellaria media*) and common lambsquarters (*Chenopodium album*) (Table 2.2). Other broadleaves included velvetleaf (*Abutilon theophrasti*), pigweed (*Amaranthus spp.*), wild mustard (*Sinapis arvensis*), field bindweed (*Convolvulus arvensis*), wild carrot (*Daucus carota*), and Pennsylvania smartweed (*Polygonum pensylvanicum*

L.). Grasses were not identified to genus and species but were counted and composed approximately 68% of all weeds sampled.

The diversity of the weed community was determined from the collected weed count data with the Shannon Wiener diversity index (H’), using the following equation:

$$H' = \frac{N \ln N - \sum n \ln n}{N}$$

where N is the total number of individuals per plot, and n is the number of individuals per species per plot [4].

Cash crops of soybean and corn were hand harvested each fall, and plant stands and crop yields were determined following field transect guidelines specified by Purdue University and University of Wisconsin, respectively [27, 28]. For both crops, a transect was laid between the middle two rows of the plots, and all above ground biomass was cut at ground level and taken to the lab, where plants were counted and yield was determined. The transect length for yield determinations varied with the row width the farm used. For soybean yield, transect length for Cerro Gordo, Malta and Pana was 5.5 m, 7.6 m and 4.6 m, respectively. For corn yield, transect length was 5.3 m for Cerro Gordo and Malta and 4.4 m for the two Pana sites. To determine the overall effect of treatments on cash crops, we calculated a productivity index that standardized our corn and soybean yields by using the mean correction of the data to make uniform determinations [29]. This standardized yield method has frequently been used in studies on crop sequences over variable topography and management practices [30, 31].

Statistical Analysis

Cover crop and weed density and biomass data were analyzed with the PROC GLIMMIX procedure of SAS [32] and crop yield data was analyzed with the PROC MIXED procedure of SAS [33]. For both analyses, the effect of replicate and site (location × year combinations) were considered random, and the effects of compaction and cover crop treatments were considered fixed. A negative binomial probability distribution and log link function model specification was used for the analysis of weed and cover crop variables [34]. Significance of random effects were calculated with a Wald Z test statistic using COVTEST option in the MIXED procedure. Pre-planned estimates were used for mean comparison purposes setting the probability of Type I error or alpha level (α) at 0.10. Figures were created using Sigma Plot version 12.5 from Systat Software, Inc., San Jose, California. Statistical model and SAS codes are available upon request from authors.

RESULTS AND DISCUSSION

Cover crops

For fall cover crop density, the main effects of compaction ($P \leq 0.0945$) and cover crop ($P \leq 0.0002$) were significant with no interaction present ($P \leq 0.6839$). Cover crop density was significantly greater in the NCP than CP areas and greatest in the FRhvr cover crop treatment (Table 2.3). Fall compaction limited cover crop growth by about 17%, but, by spring, the effect of compaction was no longer seen in the FRhvr treatment, which had the only overwintering cover crops of hairy vetch and cereal rye. Spring cover crop biomass in the FRhvr did not differ by compaction (Table 2.3). All soils under this study had a high shrink-swell potential, which creates a self-mulching effect over winter. This self-mulching could have minimized compaction in spring, allowing for improved cover crop growth following winter.

Weeds

Weed community composition and density were measured once in spring prior to cash crop planting and twice in summer before canopy closure, and results were analyzed by sampling time. Significant differences in weed density were only found in the spring. The two summer sampling times did not show an influence of compaction or cover crop on weed number, and this was attributed to the low weed communities present at these times, which were maintained by between-row cultivation. In spring, the cover crop treatment was significant ($P \leq 0.0001$), and the FRhvr was the only treatment that reduced weed density as the FR ad FRbw treatments had increased weed density in comparison to the control (Figure 2.1). The FR had 37% more weeds than the control while FRhvr had 32% fewer weeds than the control. Compaction did not significantly affect spring weed density overall ($P \leq 0.1544$). This lack of compaction effect contradicts our original hypothesis that more tillage would increase compaction and cause weed populations to expand, but we did not find significantly more weeds in the compacted areas. This lack of compaction effect could be explained by the potentially reduced compaction from the over winter self-mulching effect along with a higher tolerance to poor environmental conditions, like compaction, of these weedy species [12, 13]. In spring, the interaction of cover crop and compaction for weed biomass was significant ($P \leq 0.0946$). Spring weed biomass was significantly less in both CP and NCP FRhvr rotations with 48% and 75% fewer weeds than the CP and NCP control, respectively (Figure 2.2). This result suggests the benefit of the forage radish mixture with rye and hairy, specifically, for weed suppression in this organic grain system. Forage radish alone did not successfully suppress weed communities, likely due to its winter suppression in this Midwest region. Lawley et al. [35] researched the addition of forage radish as a winter cover crop into conventional corn production in Maryland and found forage radish's potential to suppress weeds greatly depended on planting time. When forage radish was planted early and had the necessary time to establish, spring weed populations were controlled prior to corn planting. In our study, the forage radish alone and with buckwheat may not be environmentally suited to have sufficient time to establish and effectively control weeds in this region or this particular organic system.

The FRhvr performed as the best weed suppressant with both reduced weed density and biomass, and several studies have seen weed suppression by cover crops within this treatment in monocultures in conventional systems [18-20, 35]. More research on how mixtures of cover crops compare to monocultures in organic grain production is needed. Our results echoed the research by Altieri et al. [36] in Brazil on the addition of cover crops into organic no-till bean and tomato production. The study found the mixture of forage radish, hairy vetch and cereal rye was more effective at suppressing weeds than cereal rye alone and attributed this effect to the high biomass this mixture produced that allowed shading to suppress weed populations. Our study also found this combination, FRhvr, to establish the best in term of fall density (Table 2.3). Additionally, a mixture like FRhvr allows for an extended growth period with the combination of species that thrive in fall and can overwinter to spring. A mixture holds the potential to produce more biomass, cover bare ground longer throughout the year, and provide multiple ecosystem services, like nitrogen fixation from legumes, nitrogen scavenging from grasses, and weed suppression from direct competition and/or allelopathic chemicals [37].

To further investigate the influence of the compaction and cover crop treatments on weed populations, we divided weed counts into broadleaves and grasses to determine if weed groups were affected differently. When divided into broadleaves and grasses, no differences were found from the cover crop or compaction treatments at any sampling times. Broadleaf weed count averages were 294 per m^2, 37 per m^2, and 12 per m^2, and grass weed count averages were 28 per m^2, 18 per m^2, and 3 per m^2 in spring and the two summer sampling times, respectively. This result suggests that cover crops were not selectively controlling either group, and that suppression was equally affecting the entire weed community. The Shannon Wiener Diversity Index was used to provide further insight to how these cover crops influence weed composition, and it was calculated from the weed counts and species identification at each sampling time. No significant differences were found between the main effects or interactions of compaction and cover crop treatments in spring or summer. The diversity index averaged 0.5, 0.3, and 0.1 in spring and the two summer sampling times, respectively. Like what we found in the broadleaf and grass counts groups, these cover crops were not selective on certain species as diversity did not differ by treatment. In a laboratory study, Burgos and Talbert (2000) determined the allelopathic chemicals in cereal rye suppressed small seeded weeds better than large seeded weeds. This result suggests that cereal rye would pair well in a large seeded cash crop system, like corn, as it would impair the small seeded weeds but not harm the crop [38]. Cover crops can be selective on certain weedy species, but this result was not found in our study. Additionally, more factors exist and interact in a field setting, which can interfere with this effect, but this lack of selectivity could have all been attributed to the low weed populations and low diversity indexes in this field setting. The trend appears that the cover crops in our study primarily suppress weeds through competition for valuable space and resources, and this suppression is felt evenly throughout the weed community [17].

Yields

In 2012, the interaction between compaction and cover crop was significant for soybean yields ($P \leq 0.0936$), and the NCP FRhvr rotation yielded 20% less than the NCP control (Table 2.4; Figure 2.3). A negative competitive effect between cover crop and cash crop has been discussed and seen the literature [21]. Additionally, 2012 weather conditions in Illinois were especially dry as the Midwest experiences summer temperatures that were 20-30% higher than the long-term averages [39] (Table 2.1). While cover crops have shown benefit in harsh conditions, the drought conditions in this study increased water stress and the preceding cover crops potentially hindered the following cash crop by using up the limited water available [15]. These high producing biomass mixtures can effectively suppress weeds through competition but can be limiting valuable water resources for the following soybean. Additionally, this effect was only witnessed in the NCP areas, and this could be attributed to the increased water retention in the CP areas as the compaction reduces soil pore space, which can conversely increase the capillary hold of water in the soil [9]. The compaction may have benefited the cash crop in the harsh drought years when the cash crop was strongly competing with the FRhvr treatment for water. In 2013, the main effects and interaction of compaction and cover crops were not significant for corn yields (Table 1.3).Weather conditions were relatively normal so the water stress environment was not observed, like in the soybeans in 2012 (Table 1.1). Corn yields appeared to trend similarly to the previous year's soybean yields, but the differences between treatments were not statically significant. To observe treatment effects on overall crop productivity from both years, a production index was created from the soybean and corn yields, using the mean correction of this data [29]. The interaction between cover crop and compaction was significant for the scaled yields ($P \leq 0.0860$), and these scaled yields followed the 2012 soybean trend with the NCP FRhvr treatment having significantly reduced yields (Figure 2.4). This result suggests that overall grain production is reduced in the FRhvr treatment in non-compacted areas, but this effect is exaggerated in environmentally stressed years.

CONCLUSION

Compaction did not have a significant influence overall on cover crop growth but did have an effect on spring weed biomass. Spring weed biomass was lowest in the NCP FRhvr rotation, and the FRhvr cover crop treatment had the fewest number of weeds with 37% less than the control. The FRhvr rotation was the only treatment to reduce density and biomass, but this effect was only witnessed in the first spring sampling time prior to seedbed preparation and planting. Weed suppression by cover crops was over the entire weed community as cover crop did not selectively suppress specific weed groups and did not influence weed diversity. Certain cover crop species combinations can effectively control weeds in organic grain production, but trade-offs must be considered with their implementation. In harsh weather conditions, cover crops potentially transpired valuable water resources making them unavailable for the following cash crops. The drought conditions in 2012 played a role in the 20% yield decrease in the FRhvr in NCP in comparison to the NCP control. This trend was verified with the scaled corn and soybean yields.

Overall, there is a need for more research on cover crops for the organic grain sector. Cover crop research has been frequent in conventional systems, but few studies have focused on organic production and even less on organic grain on-farm research. Our study shows that cover cropping can help improve weed management for farmers in the Midwest in organic grain production, but understanding the impact of the practice in variable weather conditions and in long term systems requires further research to help farmers manage trade-offs between risks and benefits.

TABLES AND FIGURES

Table 2.1 30- year normal monthly mean air temperature and monthly total precipitation and departure from the mean during the 2012 and 2013 growing seasons near Cerro Gordo (Urbana station), Malta (DeKalb station), and Pana, IL (Urbana station).

Month	**Cerro Gordo & Pana**			**Malta**		
	30-yr normal†	**Departure**		**30-yr normal†**	**Departure**	
		2012	**2013**		**2012**	**2013**
Jan.	-4.0	3.7	2.3	-6.5	3.2	1.9
Feb.	-1.7	3.3	0.4	-4.0	2.8	-0.9
Mar.	4.4	8.0	-3.1	2.2	8.7	-3.9
Apr.	11.1	1.4	-0.7	9.1	0.9	-1.8
May	16.9	3.6	1.1	15.2	3.2	1.4
June	22.3	0.3	-0.5	20.8	0.9	-1.0
July	23.9	3.7	-1.1	22.8	2.0	-1.5
Aug.	23.0	0.1	-0.1	21.8	-0.9	-0.6
Sept.	19.0	-1.2	1.6	17.4	-1.7	0.2
Oct.	12.2	-1.5	0.3	10.6	-1.3	-0.1
Nov.	5.2	-0.5	-1.5	3.4	-0.3	-1.9
Dec.	-1.7	4.2	-0.9	-4.2	5.0	-2.2
Year avg.	10.9	2.1	-0.2	9.1	2.8	-0.9
Precipitation (mm)						
Jan.	52	36	19	36	-10	58
Feb.	54	-18	37	39	8	24
Mar.	73	-24	-35	58	-12	-12
Apr.	93	-57	88	83	-15	125
May	124	-34	-5	116	-35	-24
June	110	-64	25	105	-86	93
July	119	-105	-31	111	-49	-68
Aug.	100	42	-88	111	-50	0
Sept.	80	63	-67	83	-44	-48
Oct.	83	55	23	73	20	9
Nov.	93	-62	-58	69	-47	-5
Dec.	69	-4	-2	55	-3	-21
Year total	1051	-172	-94	939	-323	131

Source: Water and Atmospheric Resources Monitoring Program (WARM). [25]

Table 2.2 Dominant broadleaf weeds and grasses, included but not listed, averaged over cover crop treatments and compaction areas across Illinois locations.

Dominant Broadleaf Weeds		
Common Name	**Scientific Name**	**Percentage (%)**
2012		
Henbit	*Lamium amplexicaule*	29
Field Penny-Cress	*Thlaspi arvense*	21
Velvetleaf	*Abutilon theophrasti Medic.*	2
Pigweed	*Amaranthus spp.*	1
2013		
Chickweed	*Stellaria media*	8
Field Penny-Cress	*Thlaspi arvense*	4
Common Lambsquarters	*Chenopodium album*	2
Wild Mustard	*Sinapis arvensis*	2
All		
Henbit	*Lamium amplexicaule*	10
Field Penny-Cress	*Thlaspi arvense*	9
Chickweed	*Stellaria media*	5
Common Lambsquarters	*Chenopodium album*	1

Percentages determined from the population densities and are shown by year (2012; 2013) and combined years (All).

Table 2.3 Fall cover crop density and biomass prior to winterkill (FR, forage radish; FRbw, mix of forage radish and buckwheat; FRhvr, mix of forage radish, hairy vetch, and cereal rye) and spring cover crop biomass prior to spring tillage, only FRhvr, averaged across Illinois locations**.** Different lowercase letters indicate significant differences among treatment means at alpha=0.05.

Fall Cover Crop Density		
		Number/m^2
Cover Crop	FR	39.26 a
	FRbw	40.45 a
	FRhvr	70.46 b
Compaction	CP	43.89 a
	NCP	52.91 b
Spring Cover Crop Biomass		
		g/m^2
Compaction	CP	354.96 a
	NCP	372.52 a

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Table 2.4 Soybean yields in 2012 and corn yields in 2013, in relation to cover crop treatments (Control, no cover crop; FR, forage radish; FRbw, mix of forage radish and buckwheat; and FRhvr, mix of forage radish, hairy vetch and cereal rye) in compacted (CP) and non-compacted (NCP) areas, averaged across Illinois locations. Different lowercase letters indicate significance differences among treatment means at alpha=0.05.

		2012 Soybean	**2013 Corn**
Cover Crop	**Compaction**	**(kg/ha)**	**(kg/ha)**
Control	CP	2233 ab	10309 a
	NCP	2523 b	10236 a
FR	CP	2218 ab	10219 a
	NCP	2362 b	9671 a
FRbw	CP	2127 ab	10233 a
	NCP	2518 b	9866 a
FRhvr	CP	2242 ab	10482 a
	NCP	2025 a	9463 a

Figure 2.1 Total weed density (Number/m^2) in relation to cover crop treatments (Control, no cover crop; FR, forage radish; FRbw, mix of forage radish and buckwheat; and FRhvr, mix of forage radish, hairy vetch and cereal rye) at three consecutive sampling times, averaged over compaction areas and across Illinois locations. Different lowercase letters on top of the bars indicate significant differences among treatment means at alpha=0.05.

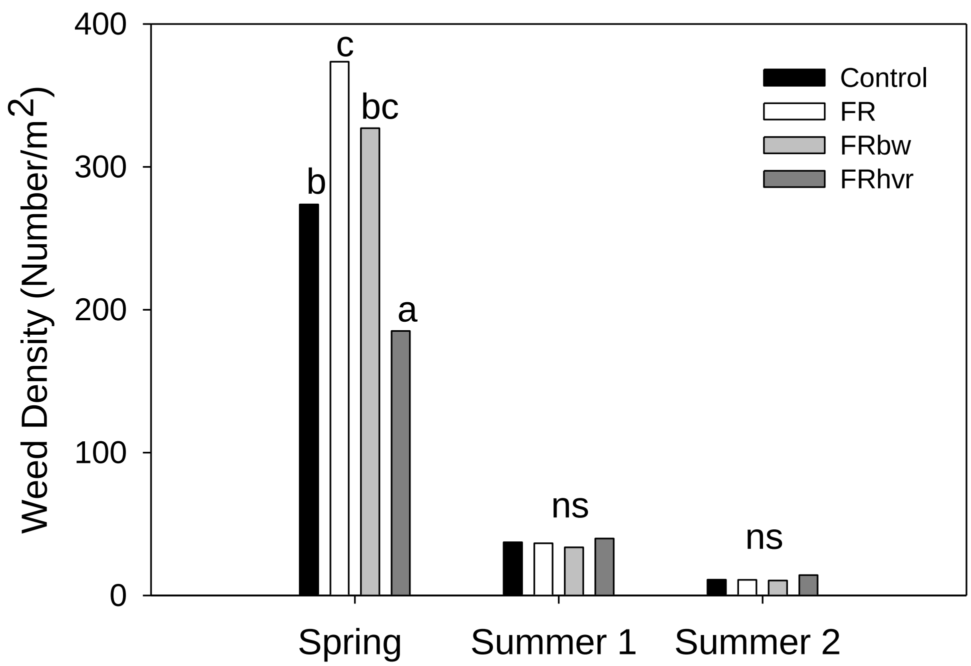


Figure 2.2 Weed biomass (g/m^2), in relation to cover crop treatments (Control, no cover crop; FR, forage radish; FRbw, mix of forage radish and buckwheat; and FRhvr, mix of forage radish, hairy vetch and cereal rye), averaged over compaction areas and across Illinois locations in spring. Different lowercase letters on top of the bars indicate significant differences among treatment means at alpha=0.05.

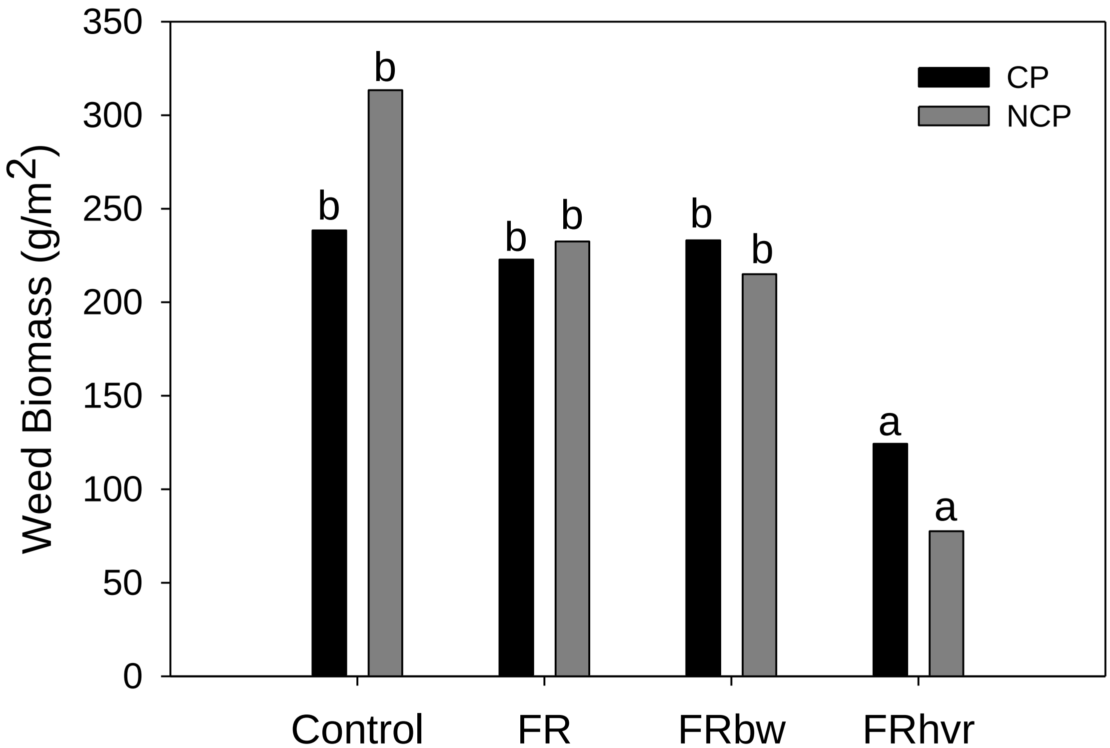


Figure 2.3 Soybean yields in 2012, in relation to cover crop treatments (Control, no cover crop; FR, forage radish; FRbw, mix of forage radish and buckwheat; and FRhvr, mix of forage radish, hairy vetch and cereal rye) in compacted (CP) and non-compacted (NCP) areas, averaged across Illinois locations. Different lowercase letters on top of the bars indicate significant differences among treatment means at alpha=0.05.

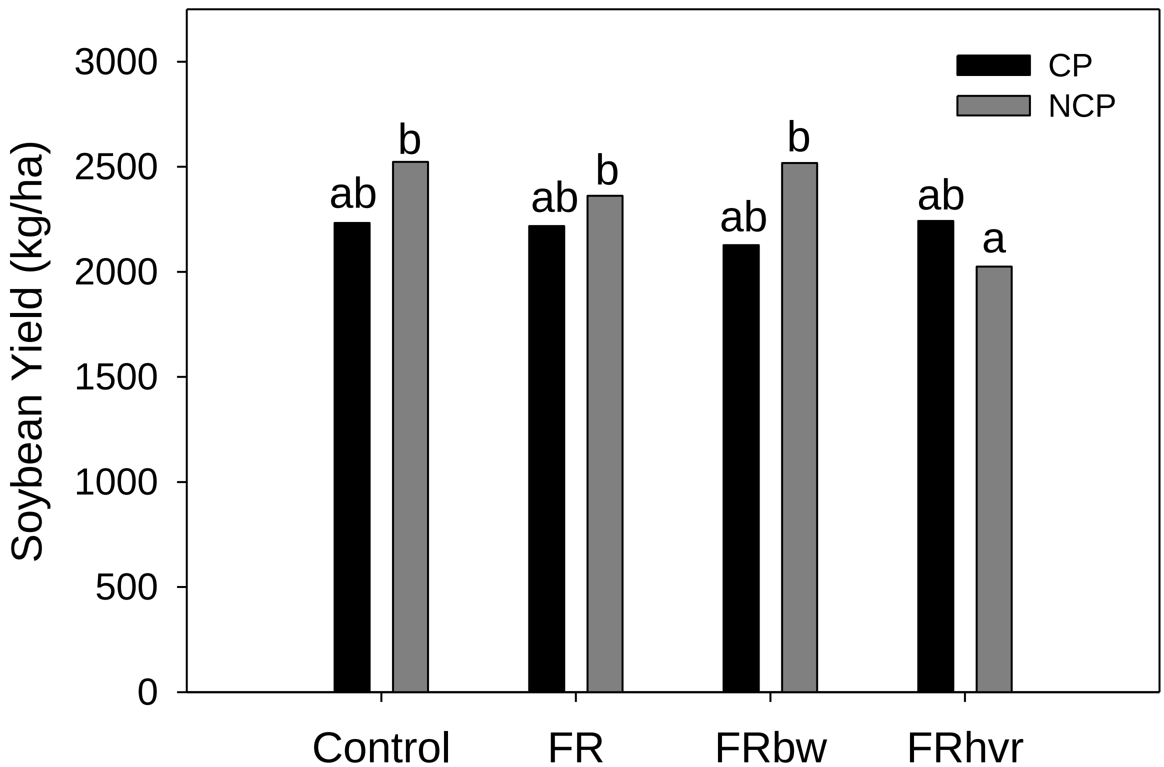
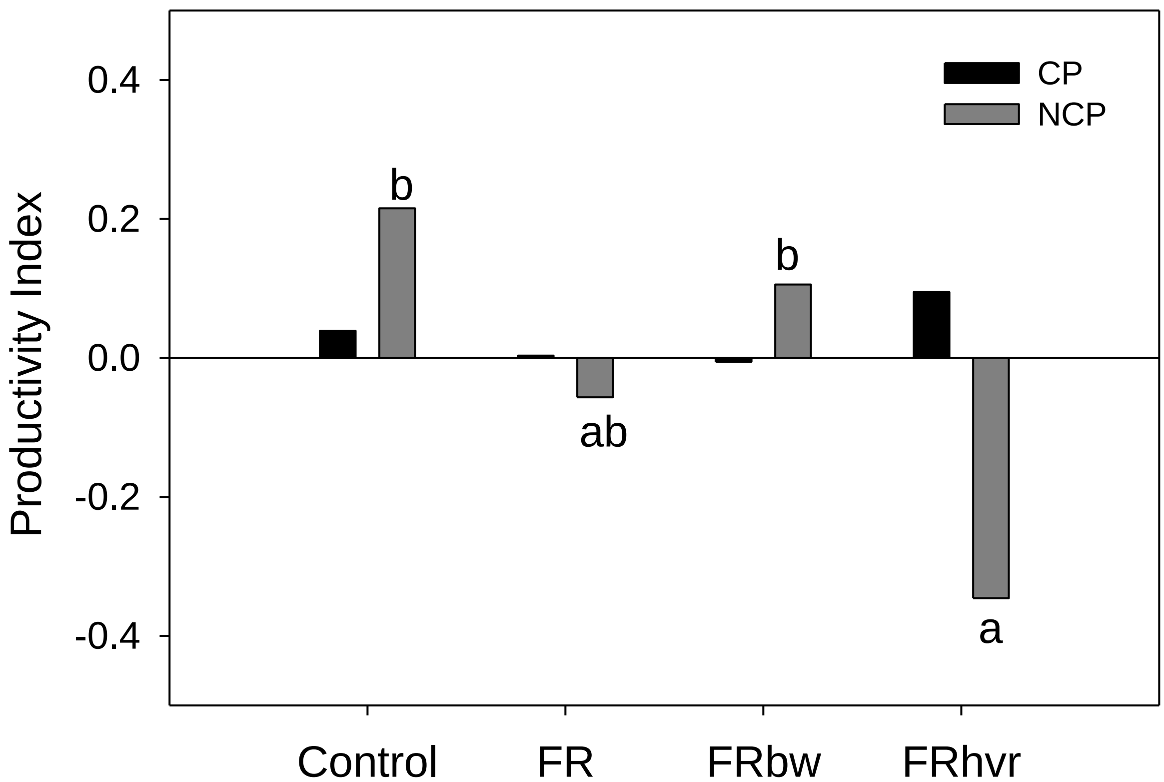


Figure 2.4 Productivity index (scaled crop yields), in relation to cover crop treatments (Control, no cover crop; FR, forage radish; FRbw, mix of forage radish and buckwheat; and FRhvr, mix of forage radish, hairy vetch and cereal rye) in compacted (CP) and non-compacted (NCP) areas averaged across Illinois locations. Different lowercase letters on top of the bars indicated significant differences among treatment means at alpha=0.05.



REFERENCES

1. Greene C, Dimitri C, Lin BH, McBride W, Oberholtzer LS, Smith TA. Emerging issues in the U.S. organic industry [Internet]. Washington, D.C. : USDA ERS; 2009 [updated 2012 May 26; cited 2015 January 13]. Available from: http://www.ers.usda.gov/publications/eib-economic-information-bulletin/eib55.aspx#.U4iybPldX0Q.

2. Sooby J, Landeck J, Lipson M. The 2007 national organic research agenda: soils, pests, livestock, genetics [Internet]. Santa Cruz, CA: Organic Farming Research Foundation; 2007 [updated 2007; cited 2015 January 13]. Available from: http://ofrf.org/sites/ofrf.org/files/docs/pdf/nora2007.pdf.

3. Davies DHK, Welsh JP. Weed control in organic cereals and pulses. Younie D, Taylor BR, Welsh JM, Wilkinson JM, editors: Chalcombe Publications; 2002.

4. Booth BD, Murphy SD, Swanton CJ. Weed ecology in natural and agricultural systems. Cambridge (MA): CABI Publishing; 2003.

5. Albrecht HH. Development of arable weed seedbanks during the 6 years after the change from conventional to organic farming. Weed Research. 2005;45(5):339-50.

6. Rydberg NT, Milberg P. A survey of weeds in organic farming in Sweden. Biological Agriculture & Horticulture: An International Journal for Sustainable Production Systems. 2000;18(2):175-85.

7. Liebman M, Davis AS. Managing weeds in organic farming systems: an ecological approach. In: Francis C, editor. Organic farming: the ecological system. Madison (WI): American Society of Agronomy, Crop Science Society of America, Soil Science Society of America; 2009. pp. 173-96.

8. Bengough AG, Mullins CE. Mechanical impedance to root growth: a review of experimental techniques and root growth responses. Journal of Soil Science. 1990;41:341-58.

9. Horn R, Domzzal H, Slowinska-Jurkiewicz A, van Ouwerkerk C. Soil compaction processes and their effects on the structure of arable soils and the environment. Soil Compaction and the Environment. 1995;35(1-2):23-36.

10. Botta GF, Tolon-Becerra A, Lastra-Bravo X, Tourn M. Tillage and traffic effects (planters and tractors) on soil compaction and soybean (*Glycine max* L.) yields in Argentinean pampas. Soil and Tillage Research. 2010;110(1):167-74.

11. Sidhu D, Duiker SW. Soil compaction in conservation tillage: crop impacts. Agronomy Journal. 2006;98(5):1257-64.

12. Reintam E, Kuht J. Weed responses to soil compaction and crop management. In: Price A, editor. Weed control. Rijeka (Croatia): InTech; 2012. pp. 244-64.

13. Place G, Bowman D, Burton M, Rufy T. Root penetration through a high bulk density soil layer: differential response of a crop and weed species. Plant & Soil. 2008;307(1/2):179-90.

14. Chen G, Weil R, Hill R. Effects of compaction and cover crops on soil least limiting water range and air permeability. Soil & Tillage Research. 2014(136):61-9.

15. Williams SM, Weil RR. Crop cover root channels may alleviate soil compaction effects on soybean crop. Soil Science Society of America. 2004;68(4):1403-9.

16. Acuna JCM, Villamil MB. Short-term effects of cover crops and compaction on soil properties and soybean production in Illinois. Agronomy Journal. 2014;106(3):860-70.

17. Managing cover crops profitably. 3rd ed. Clark A, editor. Beltsville (MD): Sustainable Agriculture Network; 1998.

18. White R, Worsham A, Blum U. Allelopathic potential of legume debris and aqueous extracts. Weed Science. 1989;37(5):674-9.

19. Dhima K, Vasilakoglou I, Eleftherohorinos I, Lithourgidis A. Allelopathic potential of winter cereals and their cover crop mulch effect on grass weed suppression and corn development. Crop Science. 2006;46:345-52.

20. Uchino H, Iwama K, Jitsuyama Y, Ichiyama K, Sugiura E, Yudate T, Nakamura S, Gopal J. Effect of interseeding cover crops and fertilization on weed suppression under an organic and rotational cropping system: 1. stability of weed suppression over years and main crops of potato, maize and soybean. Field Crops Research. 2012;127:9-16.

21. Koger C, Reddy K. Effects of hairy vetch (*Vicia villosa*) cover crop and banded herbicides on weeds, grain yield, and economic returns in corn (*Zea mays*). Journal of Sustainable Agriculture. 2005;26(3):107-24.

22. Miguez FE, Bollero GA. Winter cover crops in Illinois: evaluation of ecophysiological characteristics of corn. Crop Science. 2006;46(4):1536-45.

23. Miguez FE, Bollero GA. Review of corn yield response under winter cover cropping systems using meta-analytic methods. Crop Science. 2005;45(6):2318-29.

24. Soil Survey Staff. Web soil survey. [Internet]. NRCS-USDA; 2012 [cited 2014 May]. Available from: http://websoilsurvey.nrcs.usda.gov/.

25. Water and Atomspheric Resources Monitoring Program [database on the Internet]. Illinois State Water Survey. 2015. Available from: http://www.sws.uiuc.edu/warm/.

26. Midwest Cover Crop Council. Midwest cover crops field guide. [Internet]. West Lafayette, IN: Purdue Crop Diagnostic Training and Research Center; 2012 [updated 2012; cited 2015 January]. 2nd Edition. Available from: http://www.mccc.msu.edu/.

27. Casteel S. Estimating soybean yields - simplified. Lafayettee, IN: Purdue University; 2012 [cited 2014 September 9]. Available from:

https://www.agry.purdue.edu/ext/soybean/News/2012/2012_0814SOYSimplifiedYieldEstimates.pdf.

28. Lauer J. Methods for calculating corn yield. Madison, WI: University of Wisconsin Agronomy Department; 2002 [cited 2013 September 9]. Available from: http://corn.agronomy.wisc.edu/AA/pdfs/A033.pdf.

29. Sharma S. Applied multivariate techniques. New York: John Wiley & Sons, Inc.; 1996.

30. Eghball B, Varvel GE. Fractal analysis of temporal yield variability of crop sequences: implications for site-specific management. Agronomy Journal. 1997;89:851-5.

31. Kravchenko AN, Bullock DG. Correlation of corn and soybean grain yield with topography and soil properties. Agronomy Journal. 2000;92:75-83.

32. SAS Institute. SAS/STAT 9.1 Production GLIMMIX procedure for windows. Cary (NC): SAS Institute; 2005.

33. Littell RC, Miliken GA, Stroup WW, Wolfinger RD. SAS system for mixed models. Cary (NC): SAS Institute; 1996.

34. Gbur EE, Stroup WW, McCarter KS, Durham S, Young LJ, Christman M, West M, Kramer M. Analysis of generalized linear mixed models in the agricultural and natural resources sciences. Madison (WI): American Society of Agronomy, Soil Science Society of America, Crop Science Society of America; 2012.

35. Lawley YE, Weil RR, Teasdale JR. Forage radish cover crop suppresses winter annual weeds in fall and before corn planting. Agronomy Journal. 2011;103(1):137-44.

36. Altieri MA, Lana MA, Bittencourt HV, Kieling AS, Comin JJ, Lovato PE. Enhancing crop productivity via weed suppression in organic no-till cropping systems in Santa Catarina, Brazil. Journal of Sustainable Agriculture. 2011;35(8):855-69.

37. Hoorman JJ. Using cover crops to improve soil and water quality. Lima, Ohio: The Ohio State University; 2009 [cited 2014 December 16]. Available from: http://www.mccc.msu.edu/states/Ohio/OH_CoverCrops_to_Improve_Soi&Water_Quality.pdf.

38. Burgos NR, Talbert RE. Differential activity of allelochemicals from *Secale cereale* in seedling bioassays. Weed Science. 2000;48(3):302-10.

39. Mallya G, Zhao L, Song XC, Niyogi D, Govindaraju RS. 2012 Midwest drought in the United States. Journal of Hydrologic Engineering. 2013;18:737-45.